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(54) **CONTROL CIRCUIT FOR DC NETWORK TO MAINTAIN ZERO NET CHANGE IN ENERGY LEVEL**

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(58) **Field of Classification Search**
CPC H02M 3/158
See application file for complete search history.

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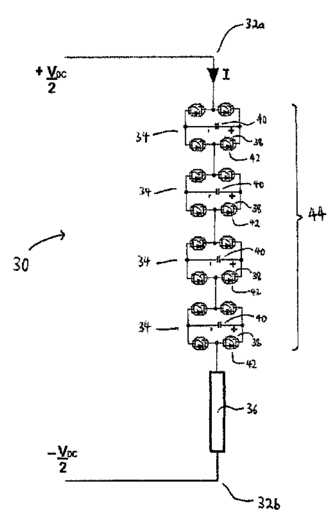
(57) **ABSTRACT**

There is a control circuit comprising first and second DC terminals for connection to a DC network, the first and second DC terminals having a plurality of modules and at least one energy conversion element connected in series therebetween to define a current transmission path, the plurality of modules defining a chain-link converter, each module including at least one energy storage device, the or each energy storage device being selectively removable from the current transmission path to cause a current waveform to flow from the DC network through the current transmission path and the or each energy conversion element and thereby remove energy from the DC network, the or each energy storage device being selectively removable from the current transmission path to modulate the current waveform to maintain a zero net change in energy level of the chain-link converter.

17 Claims, 23 Drawing Sheets



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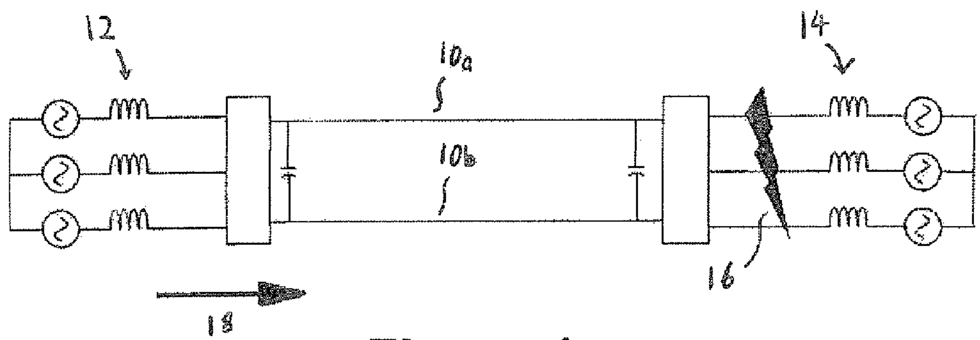


Figure 1a

(PRIOR ART)

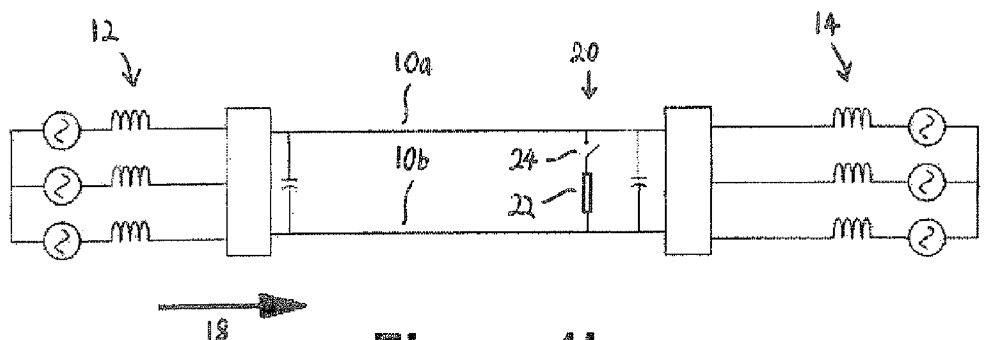
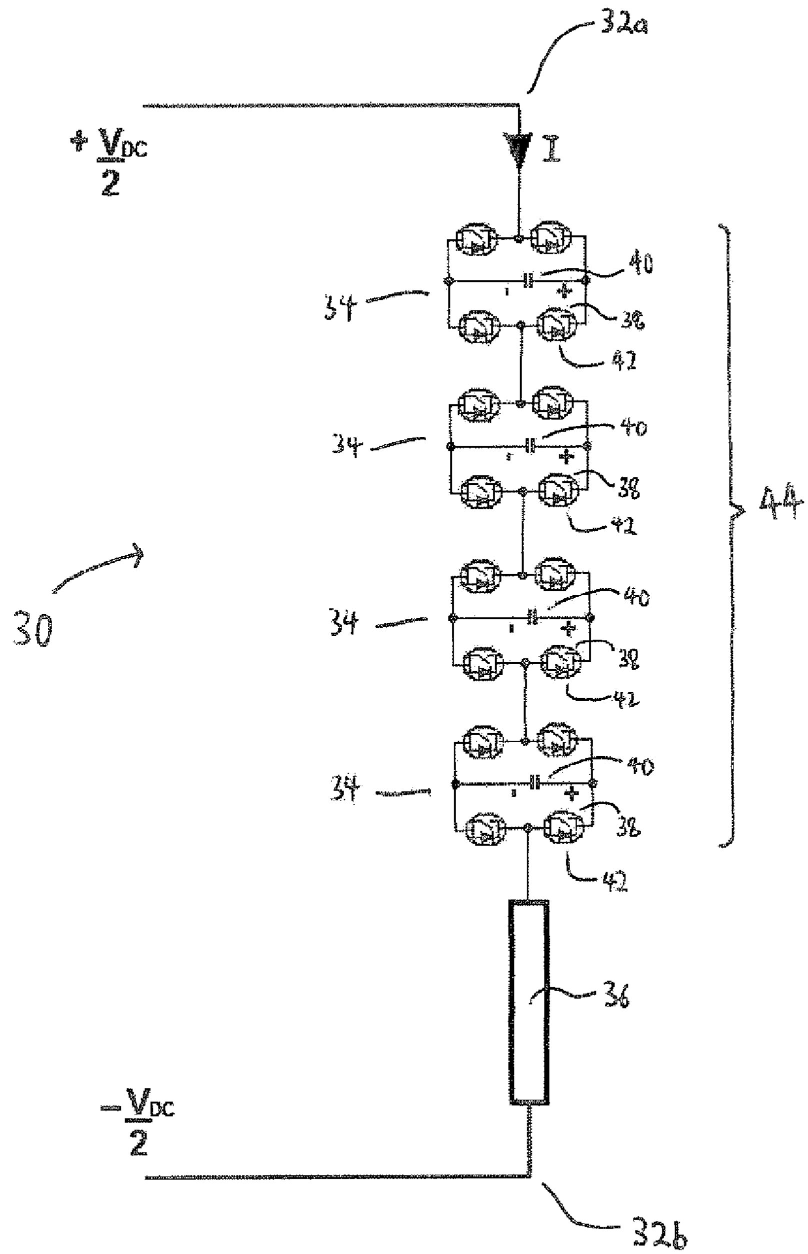


Figure 1b

(PRIOR ART)



32a
$+\frac{V_{DC}}{2}$
I
40
34
38
42
40
34
38
42
44
30
40
34
38
42
40
34
38
42
36
$-\frac{V_{DC}}{2}$
32b

Figure 2

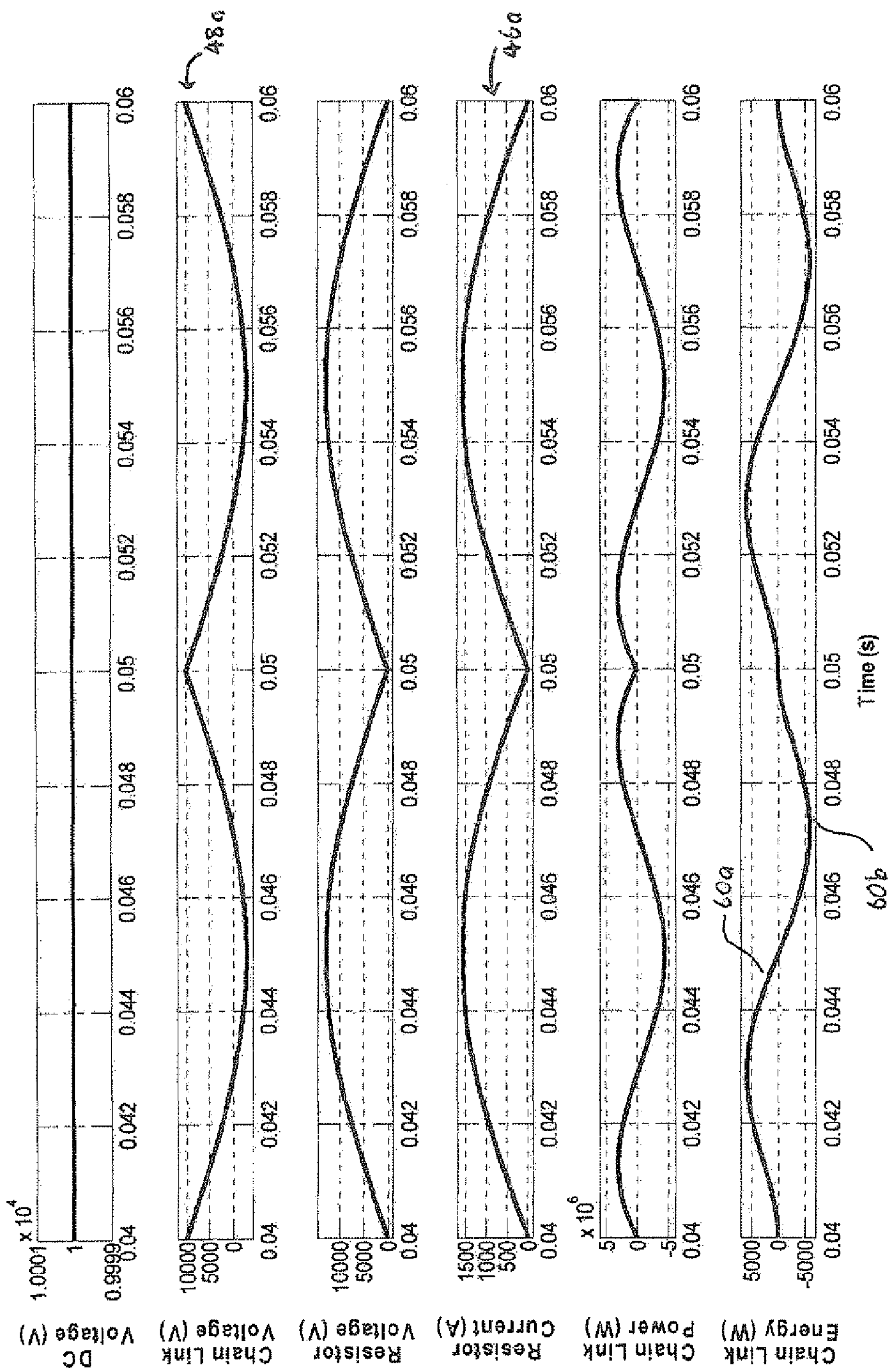
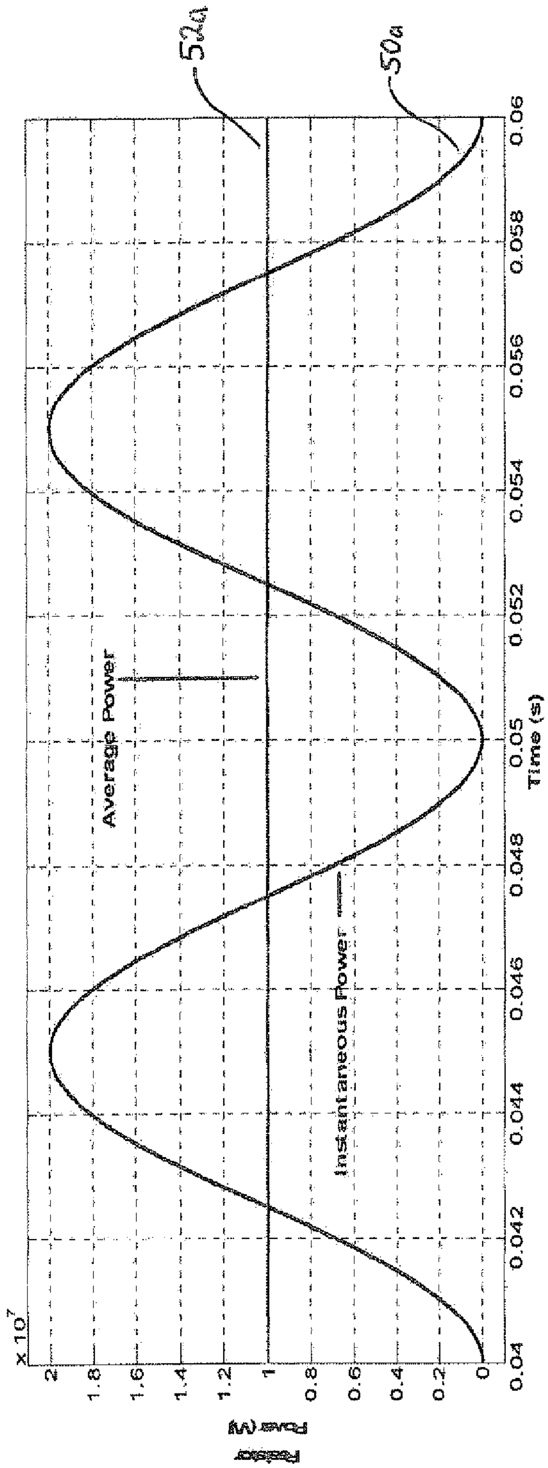
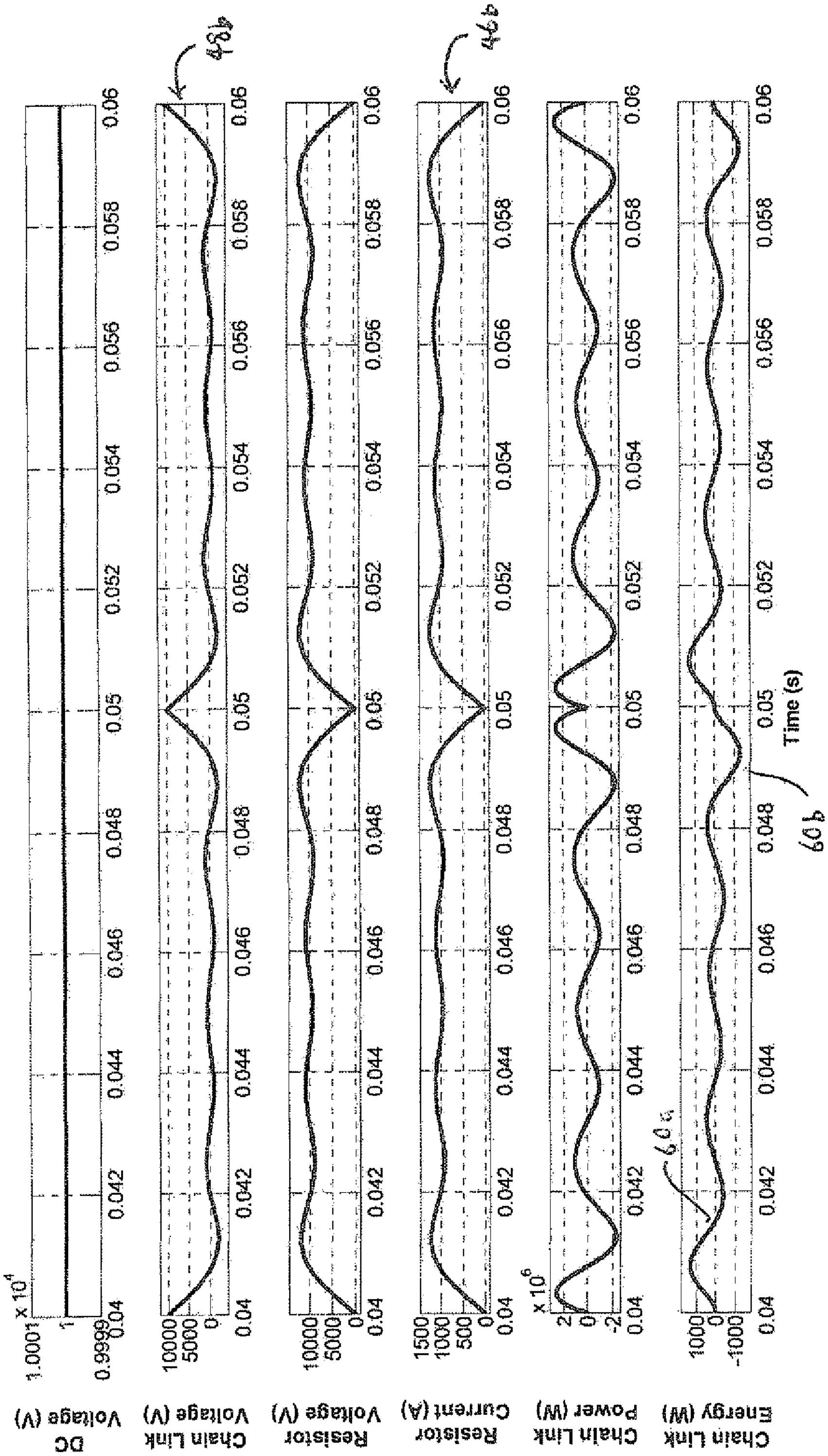

DC Voltage (V)
Chain Link Voltage (V)
Resistor Voltage (V)
Resistor Current (A)
Chain Link Power (W)
Chain Link Energy (W)
x 10^4
1.0001
1
0.9999
10000
5000
0
1500
1000
500
x 10^6
5
-5
-5000
0.04
0.042
0.044
0.046
0.048
0.05
0.052
0.054
0.056
0.058
0.06
Time (s)
48a
46a
60a
60b

Figure 3a



52a
50a
Average Power
Instantaneous Power
Time (s)
x 10^7
Resistor Power (W)
0.04
0.042
0.044
0.046
0.048
0.05
0.052
0.054
0.056
0.058
0.06
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Figure 3b



DC Voltage (V)
Chain Link Voltage (V)
Resistor Voltage (V)
Resistor Current (A)
Chain Link Power (W)
Chain Link Energy (W)
Time (s)
48b
49b
60a
60b

Figure 4a

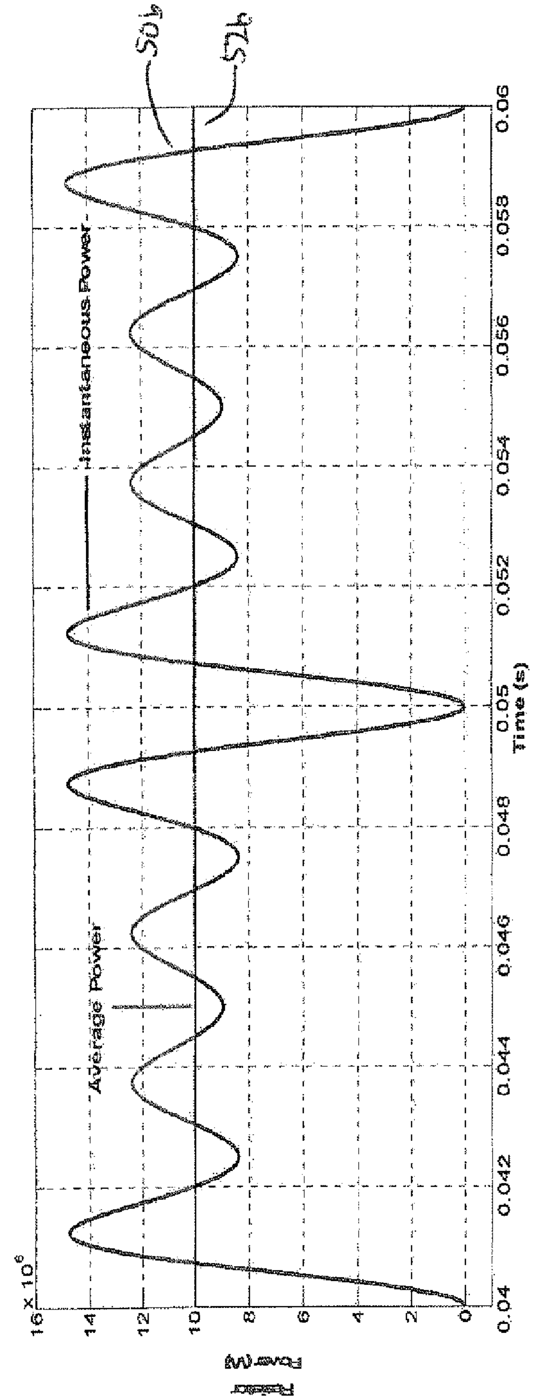

506
526
Instantaneous Power
Average Power
Time (s)
x 10^6
0.04
0.042
0.044
0.046
0.048
0.05
0.052
0.054
0.056
0.058
0.06
0
2
4
6
8
10
12
14
16

Figure 4b

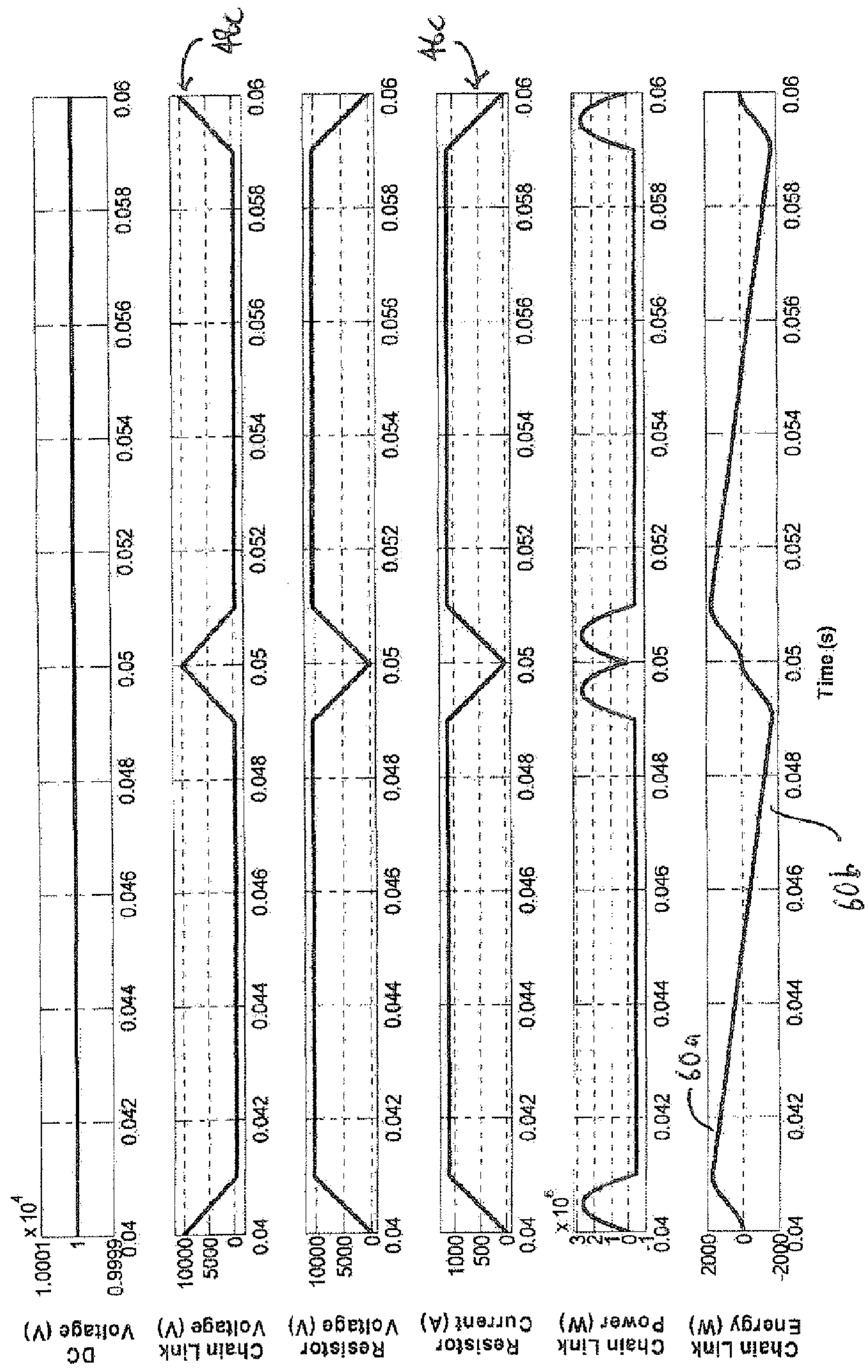

DC Voltage (V)
Chain Link Voltage (V)
Resistor Voltage (V)
Resistor Current (A)
Chain Link Power (W)
Chain Link Energy (W)
Time (s)
48c
46c
60a
60b

Figure 5a

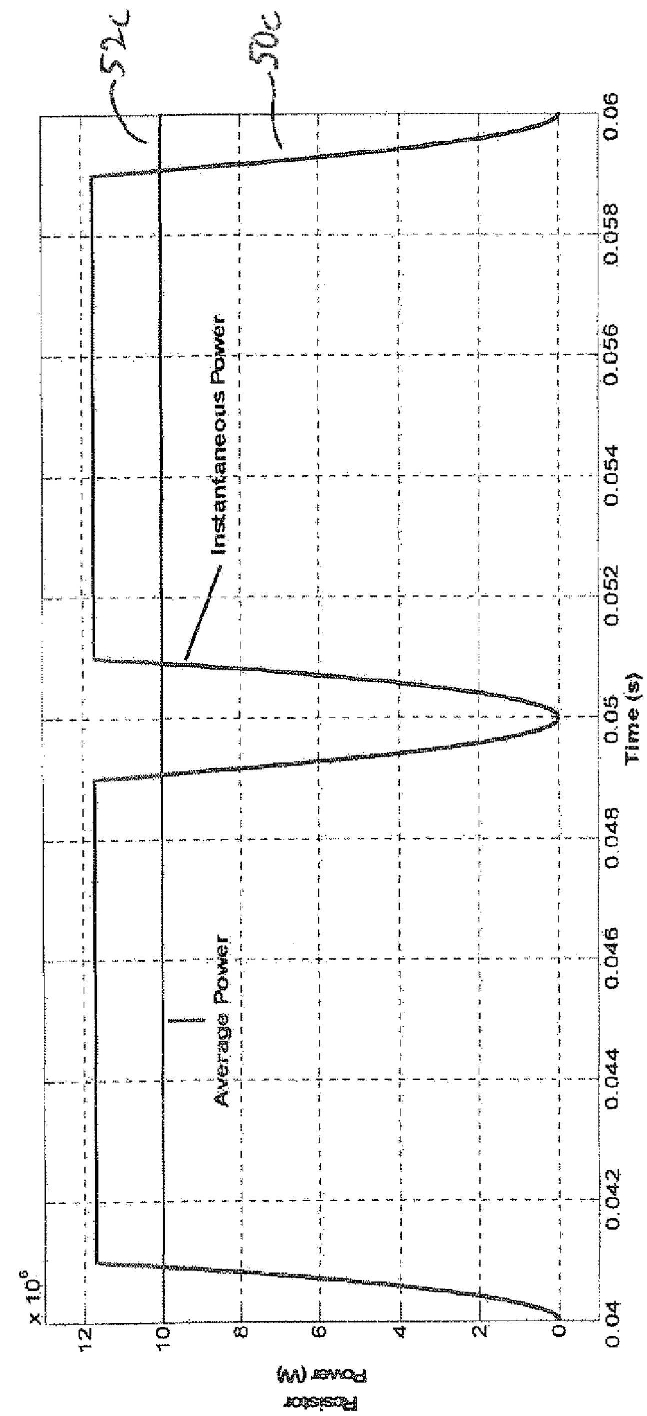

52c
50c
Instantaneous Power
Average Power
x 10^6
12
10
8
6
4
2
0
0.04
0.042
0.044
0.046
0.048
0.05
0.052
0.054
0.056
0.058
0.06
Time (s)

Figure 5b

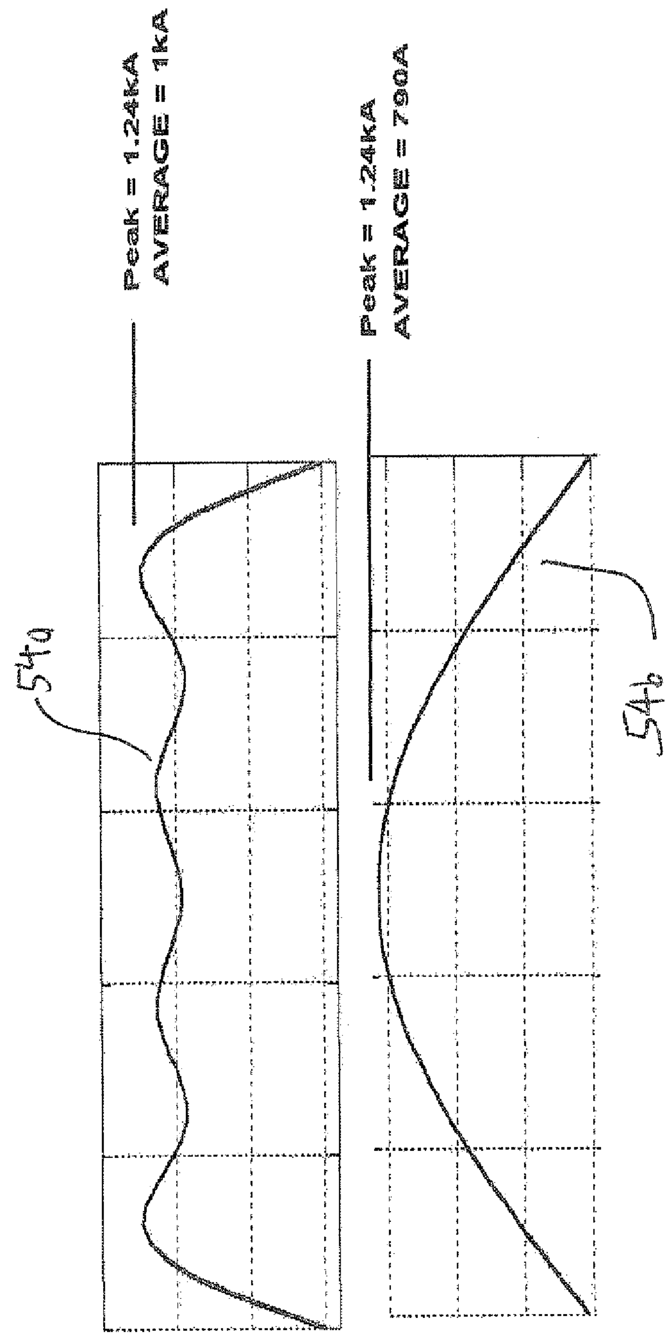


Figure 6

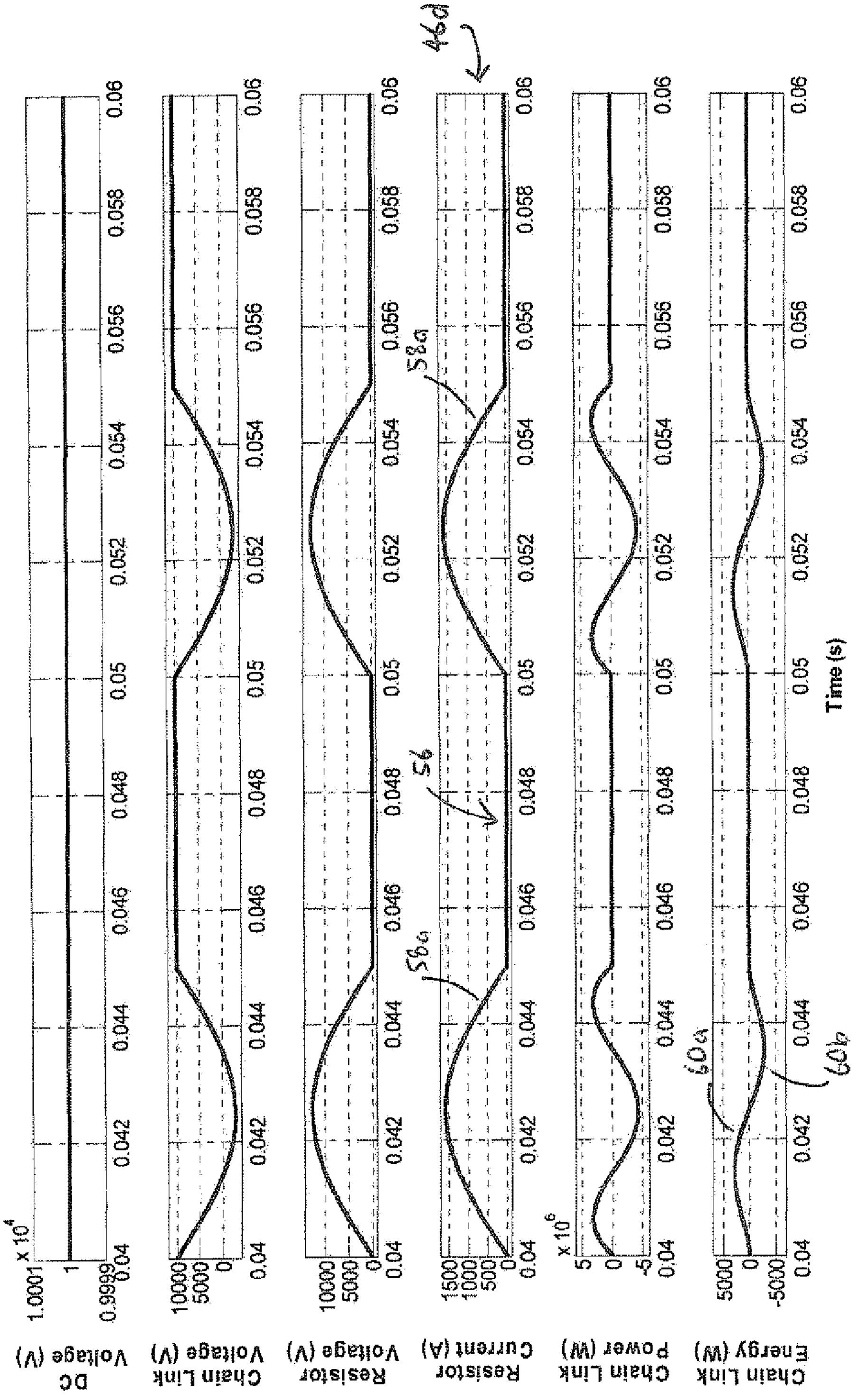

46d
DC Voltage (V)
Chain Link Voltage (V)
Resistor Voltage (V)
Resistor Current (A)
Chain Link Power (W)
Chain Link Energy (W)
58a
56
58a
60a
60b
Time (s)

Figure 7a

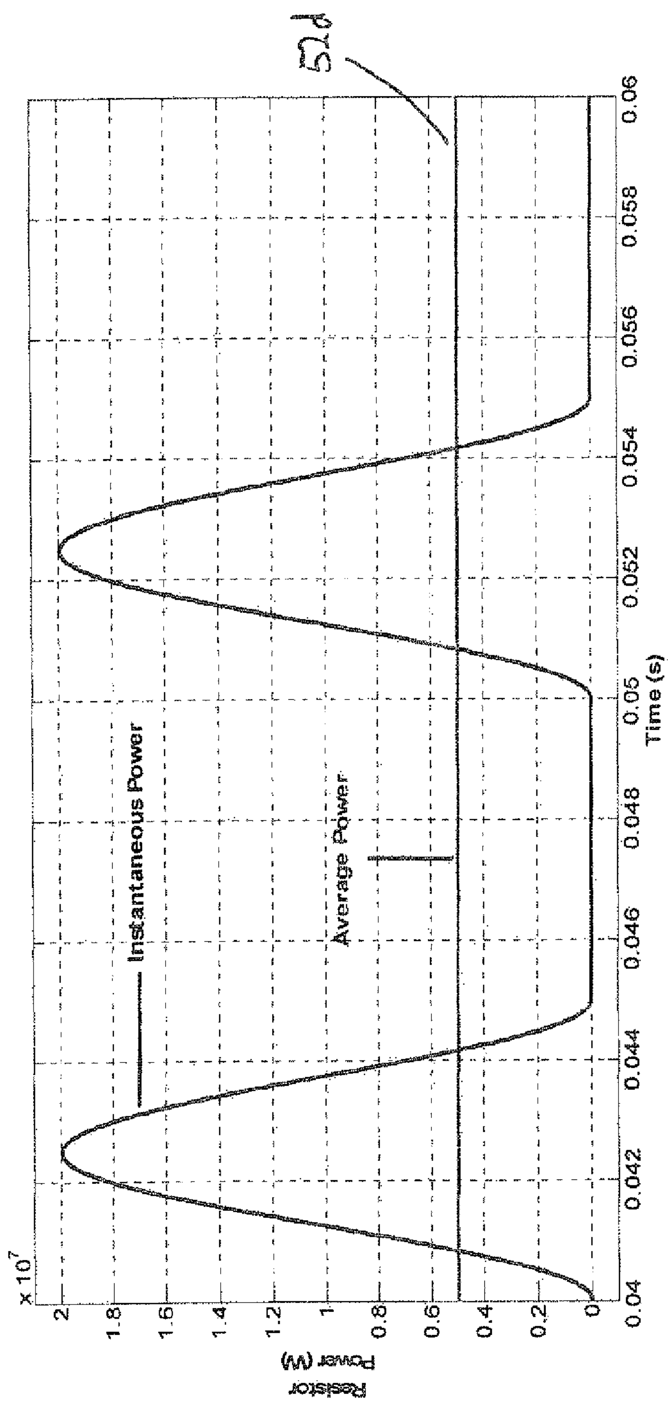

52d
Instantaneous Power
Average Power
Resistor
Power (W)
x 10^7
Time (s)

Figure 7b

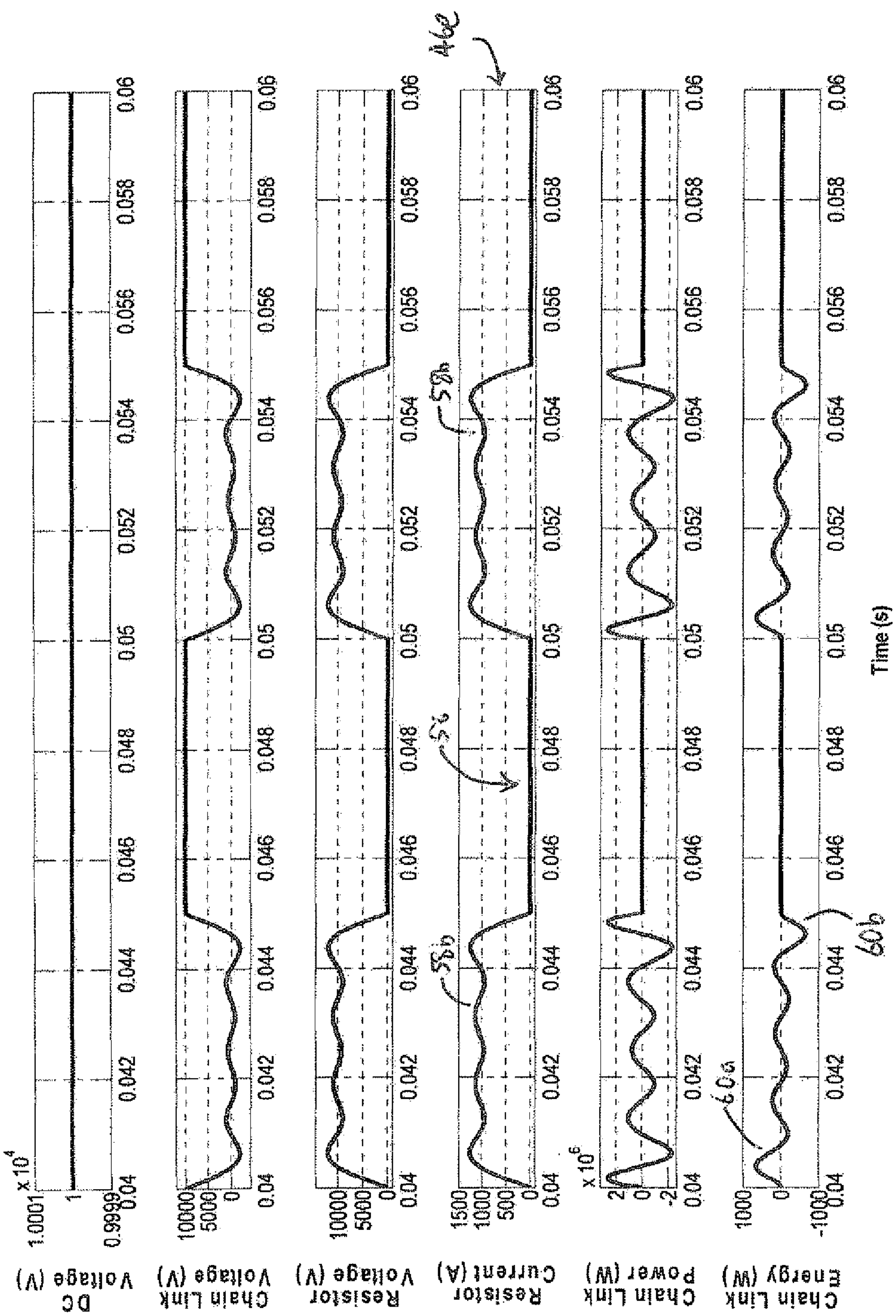

DC Voltage (V)
Chain Link Voltage (V)
Resistor Voltage (V)
Resistor Current (A)
Chain Link Power (W)
Chain Link Energy (W)
Time (s)
46e
56
58a
58b
60a
60b

Figure 8a

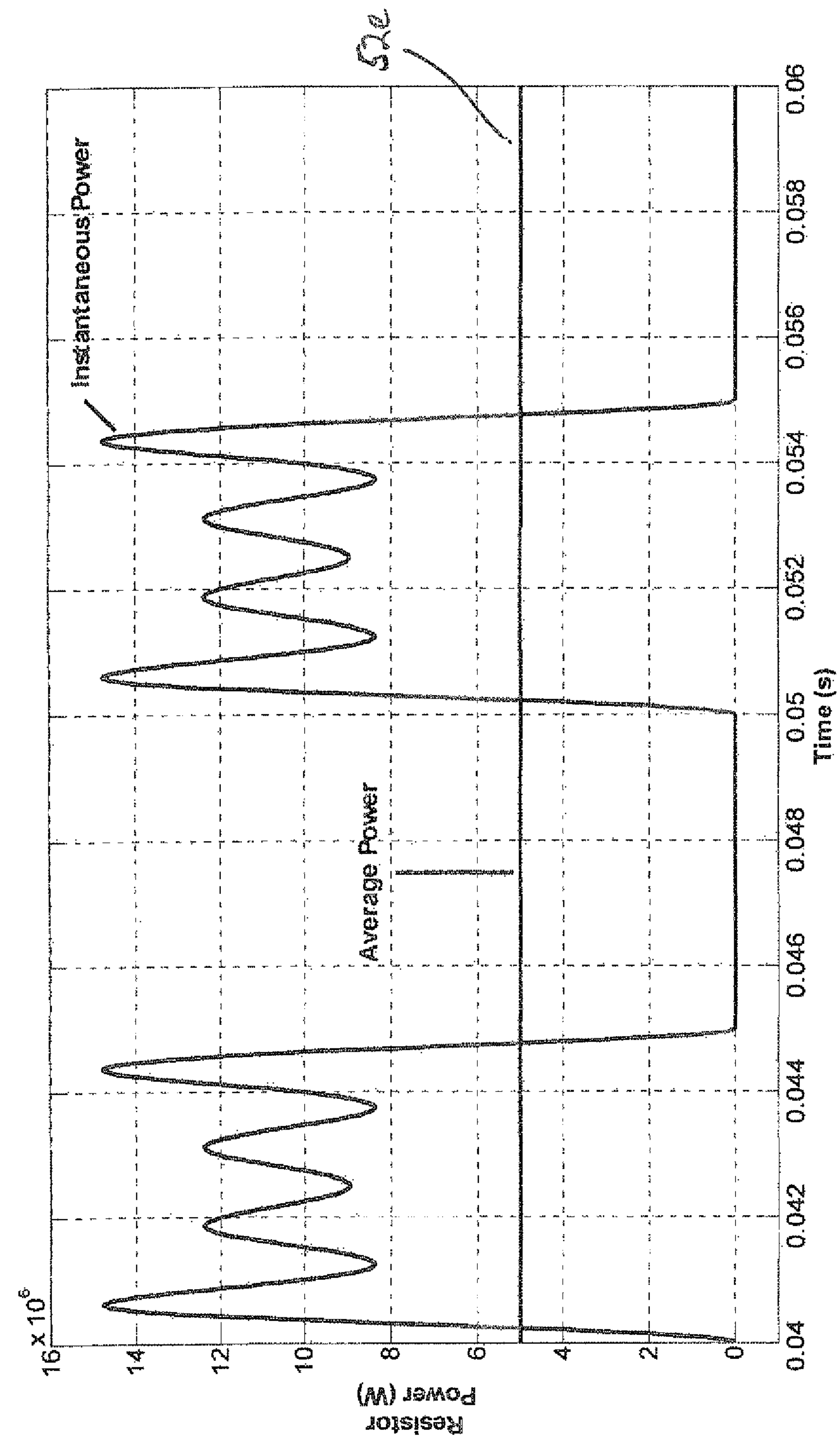

52e
Instantaneous Power
Average Power
Resistor Power (W)
x 10^6
16
14
12
10
8
6
4
2
0
0.04
0.042
0.044
0.046
0.048
0.05
0.052
0.054
0.056
0.058
0.06
Time (s)

Figure 8b

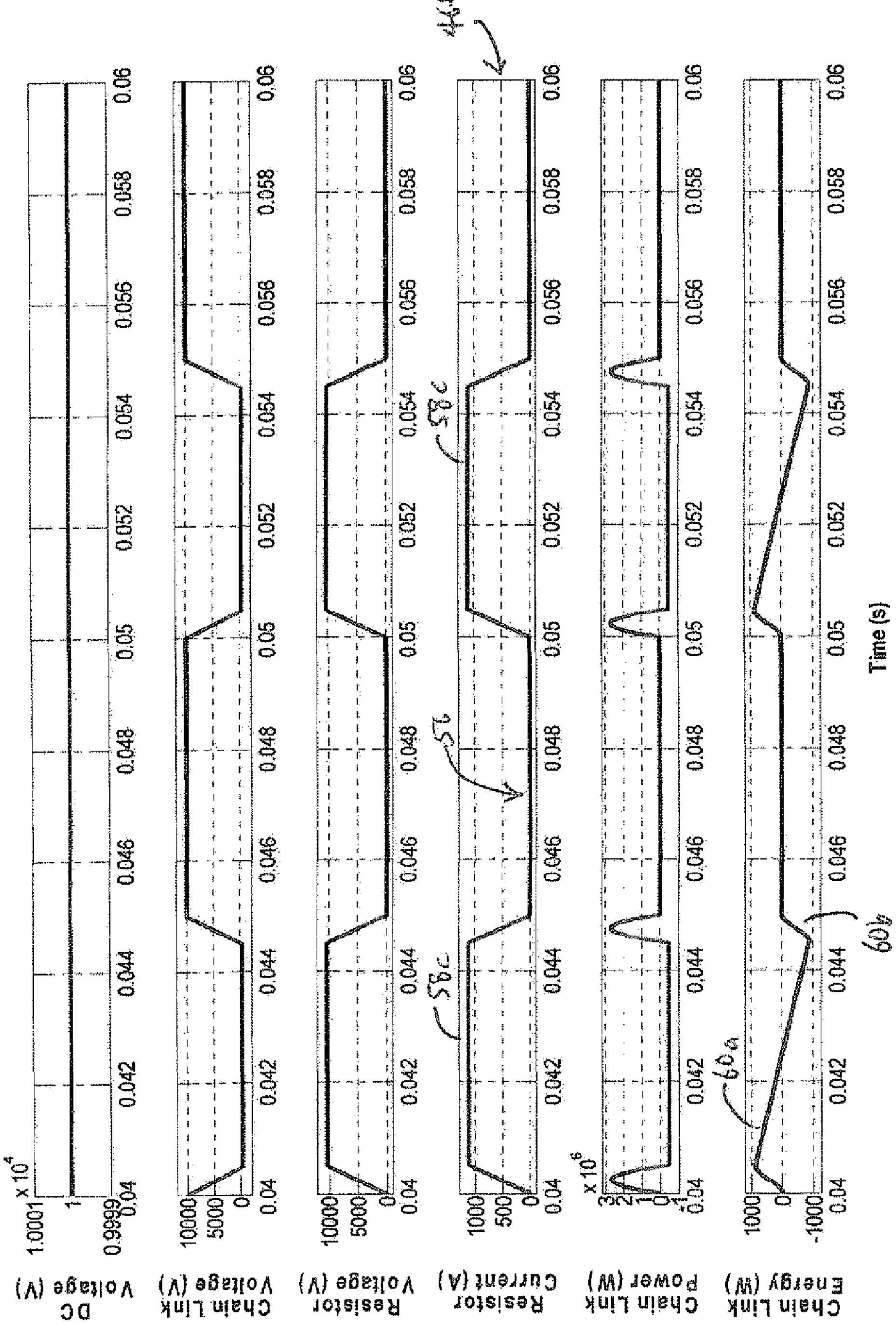

DC Voltage (V)
Chain Link Voltage (V)
Resistor Voltage (V)
Resistor Current (A)
Chain Link Power (W)
Chain Link Energy (W)
x 10^4
x 10^6
Time (s)
44f
58c
56
58c
60a
60b

Figure 9a

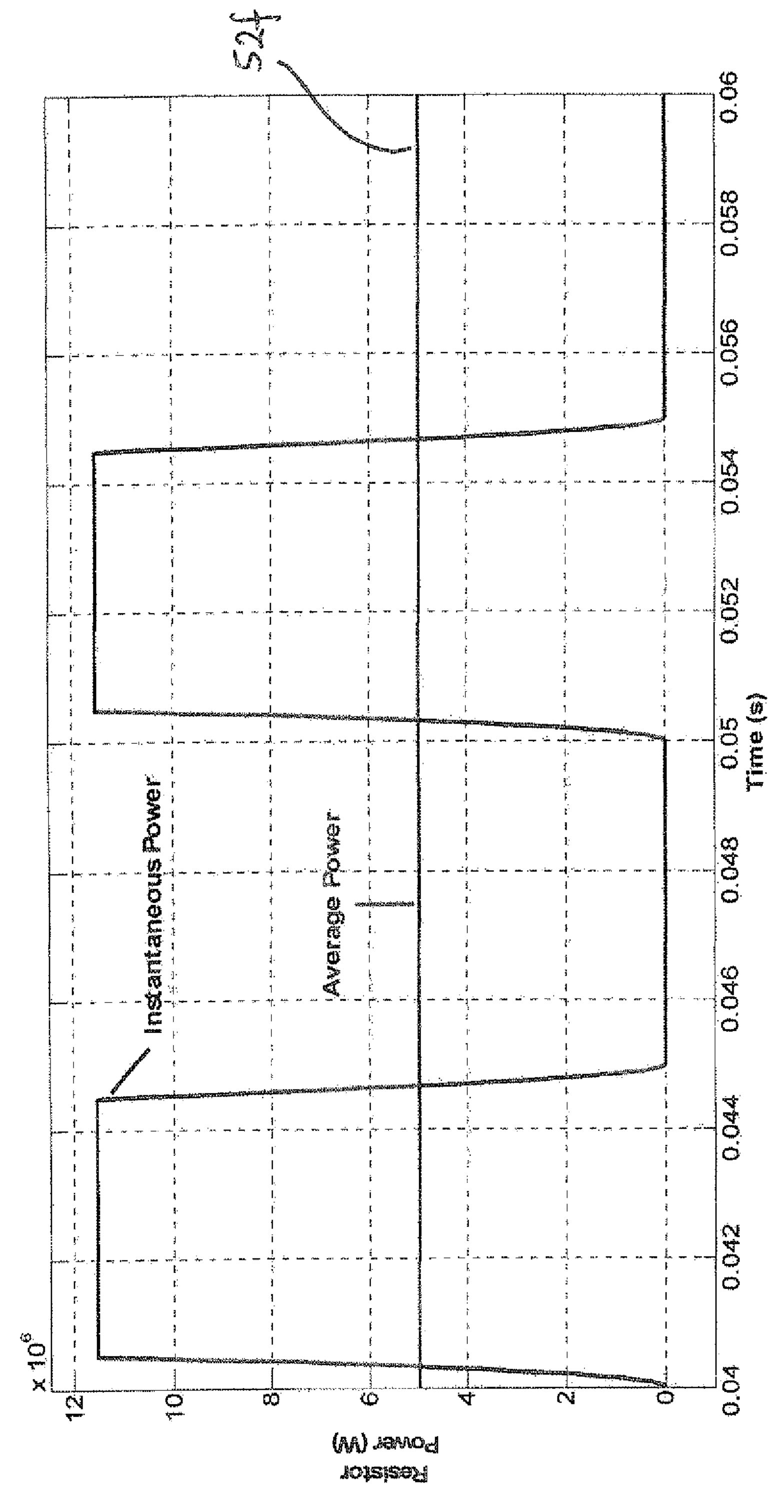

52f
Instantaneous Power
Average Power
Resistor
Power (W)
x 10^6
12
10
8
6
4
2
0
0.04
0.042
0.044
0.046
0.048
0.05
0.052
0.054
0.056
0.058
0.06
Time (s)

Figure 9b

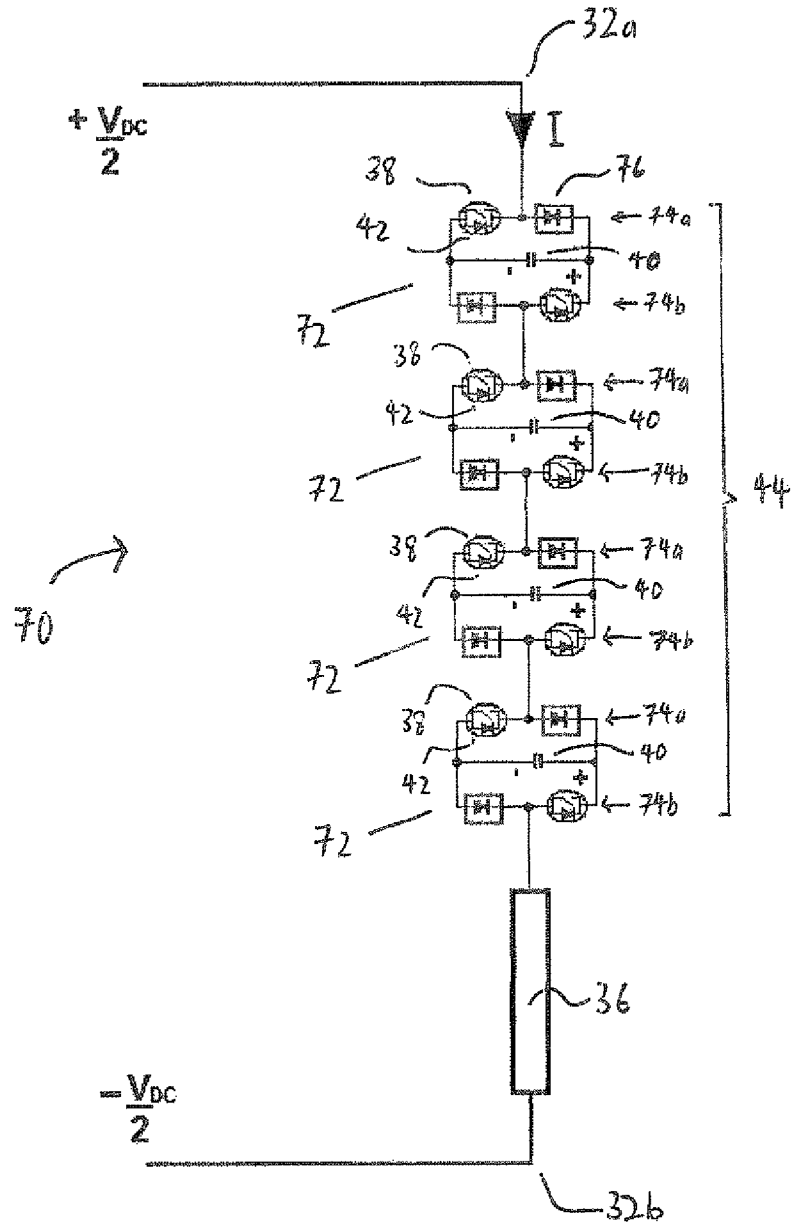


Figure 10

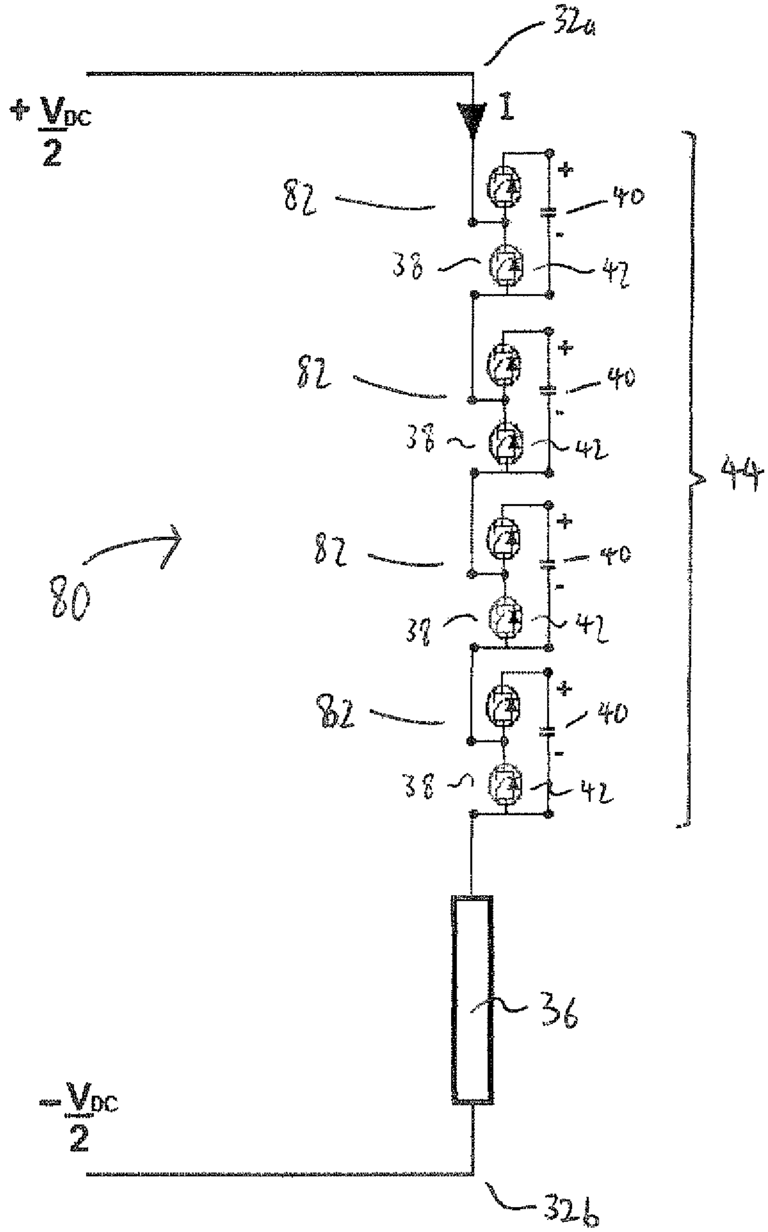
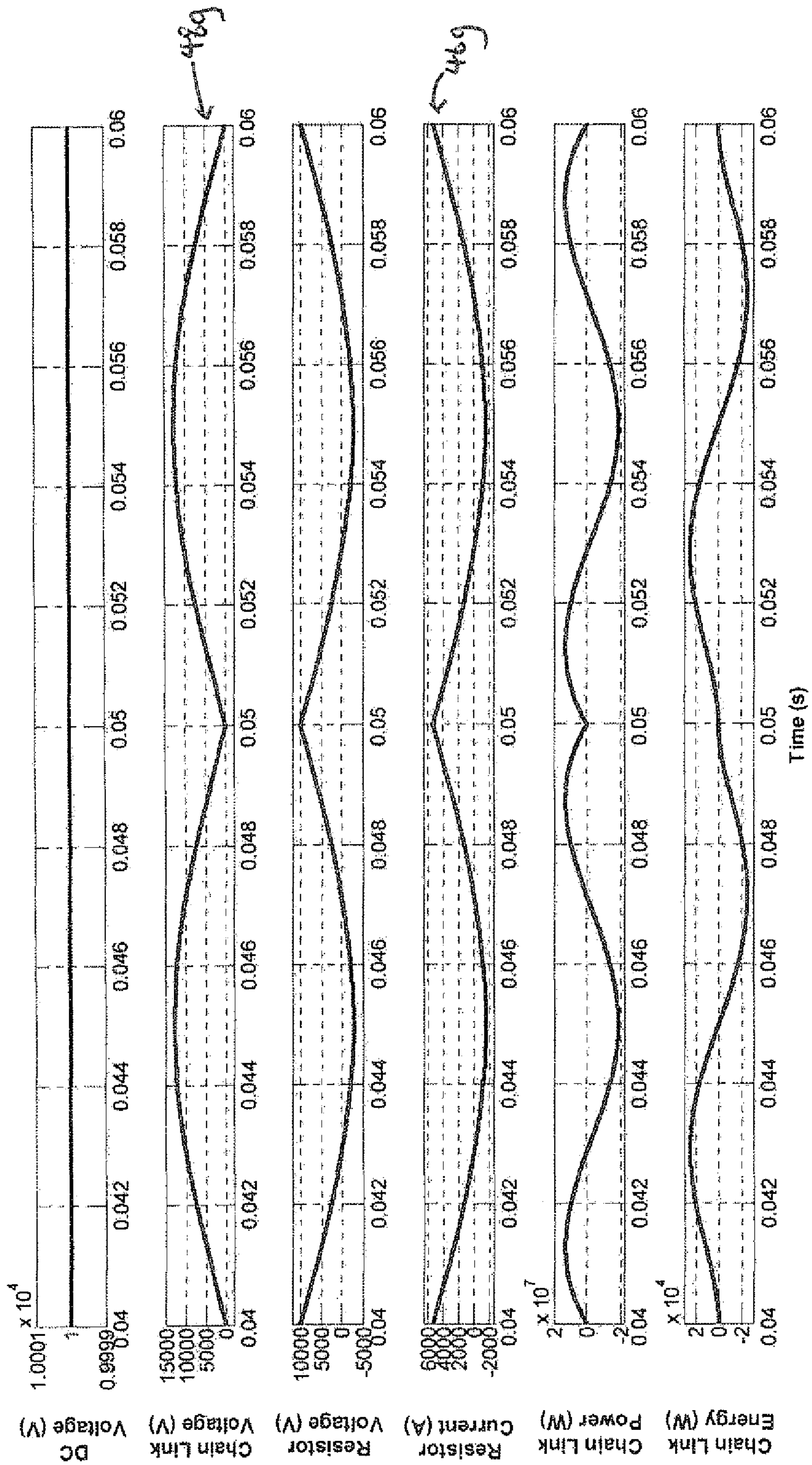


Figure 11



46g
46g
DC Voltage (V)
Chain Link Voltage (V)
Resistor Voltage (V)
Resistor Current (A)
Chain Link Power (W)
Chain Link Energy (W)
Time (s)

Figure 12a

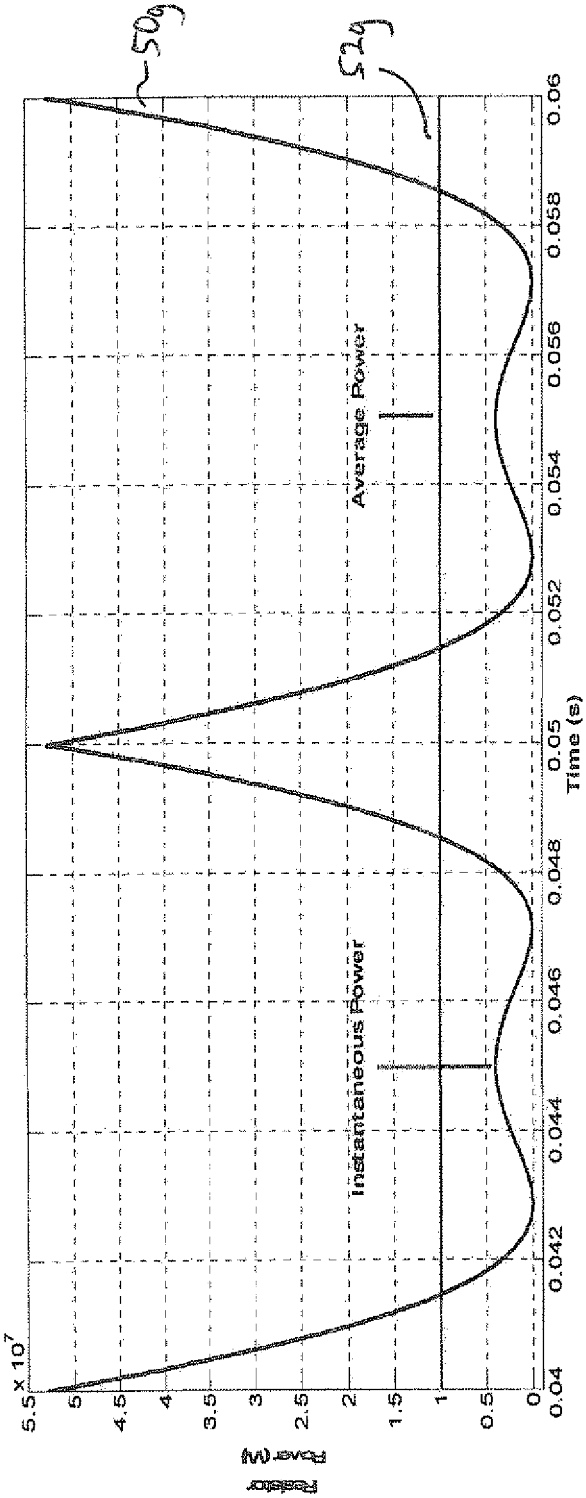

50g
52g
Instantaneous Power
Average Power
Time (s)
Resistor Power (W)
x 10^7
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0.04
0.042
0.044
0.046
0.048
0.05
0.052
0.054
0.056
0.058
0.06

Figure 12b

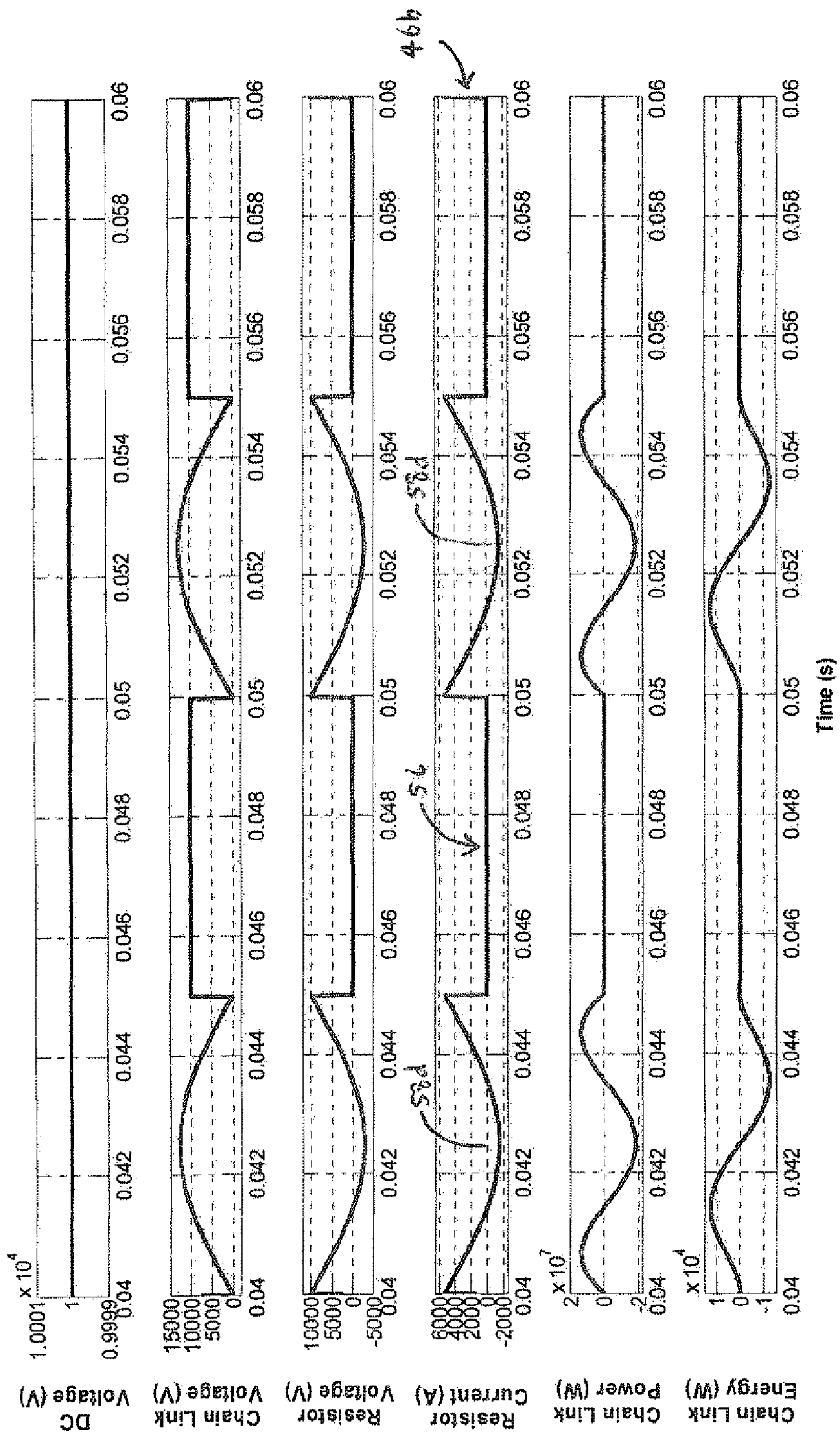

DC Voltage (V)
Chain Link Voltage (V)
Resistor Voltage (V)
Resistor Current (A)
Chain Link Power (W)
Chain Link Energy (W)
Time (s)
46b
92
92a

Figure 13a

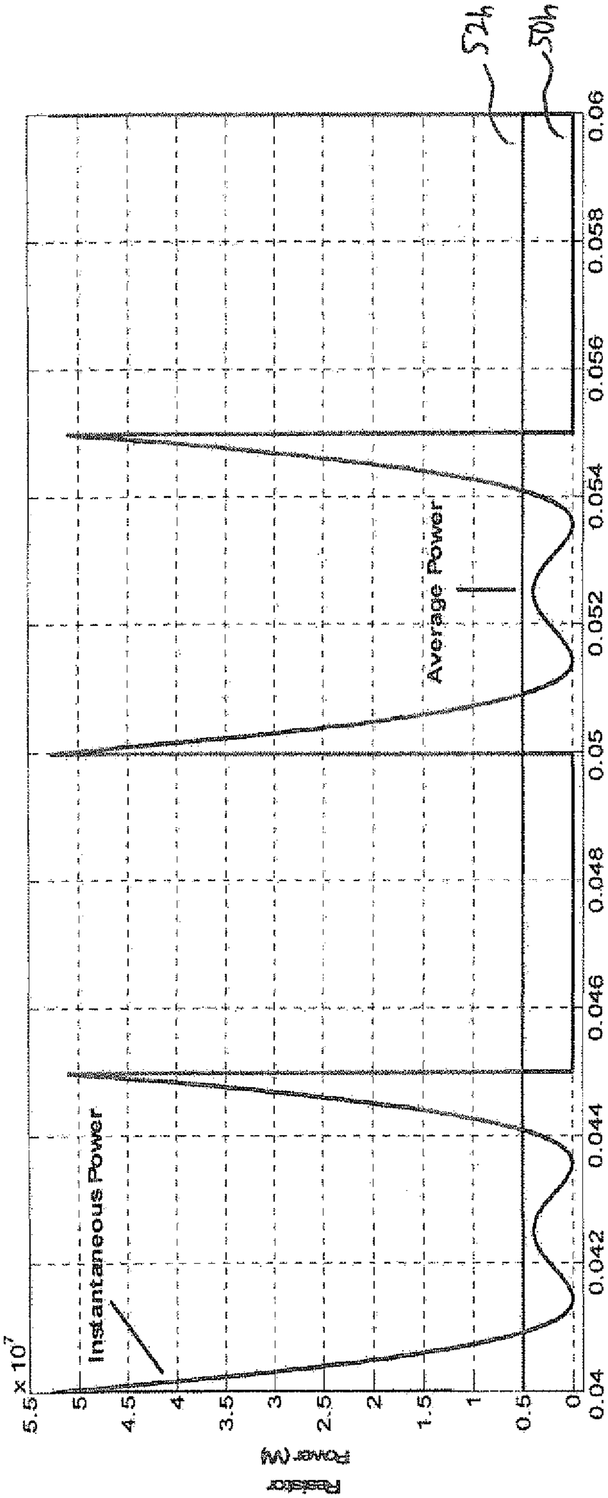

52h
50h
Instantaneous Power
Average Power
× 10^7
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Resistor Power (W)
0.04
0.042
0.044
0.046
0.048
0.05
0.052
0.054
0.056
0.058
0.06
Time (s)

Figure 13b

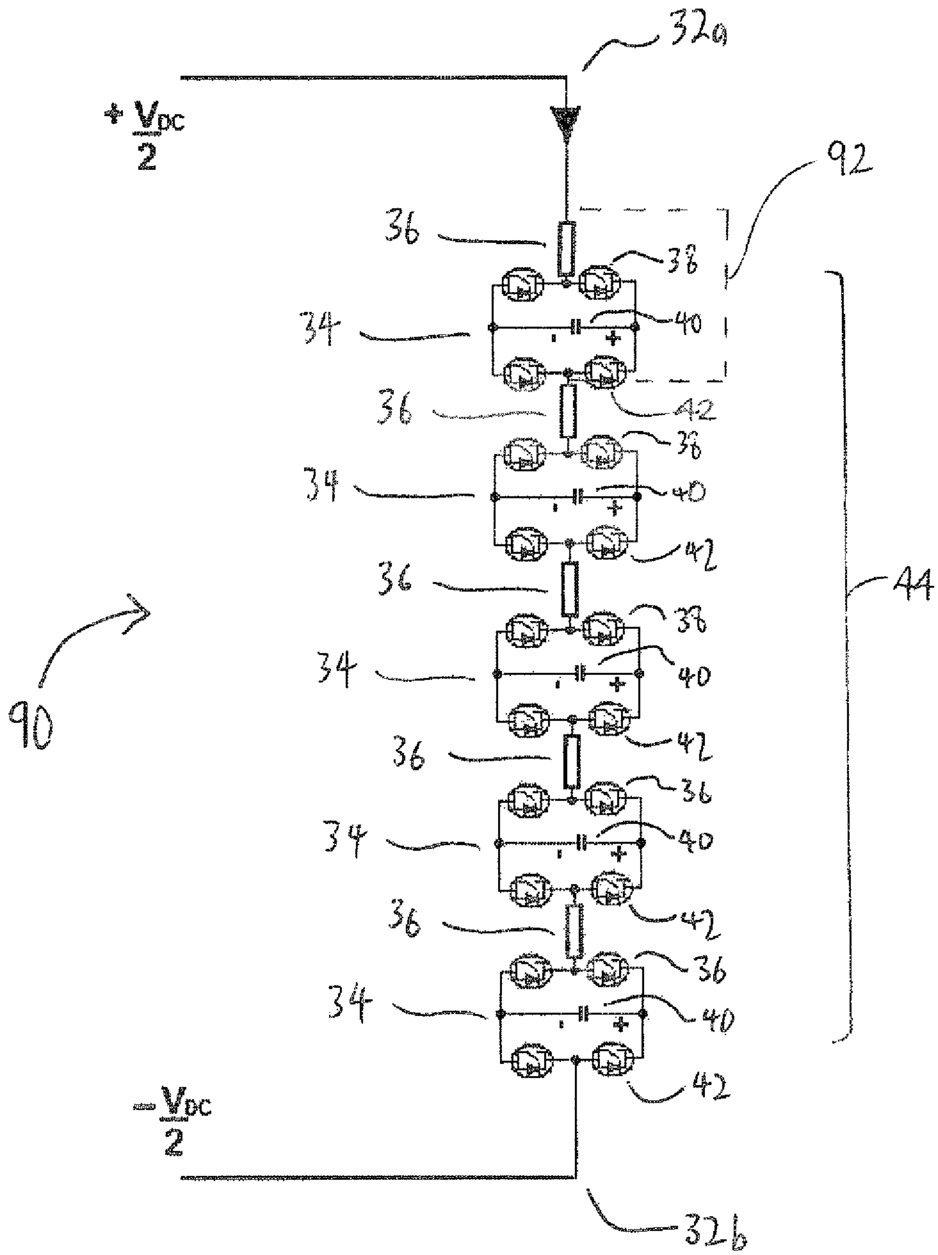

32a
$+\frac{V_{DC}}{2}$
92
36
38
34
40
42
36
38
34
40
42
44
36
38
34
40
90
42
36
36
34
40
42
36
36
34
40
42
$-\frac{V_{DC}}{2}$
32b

Figure 14

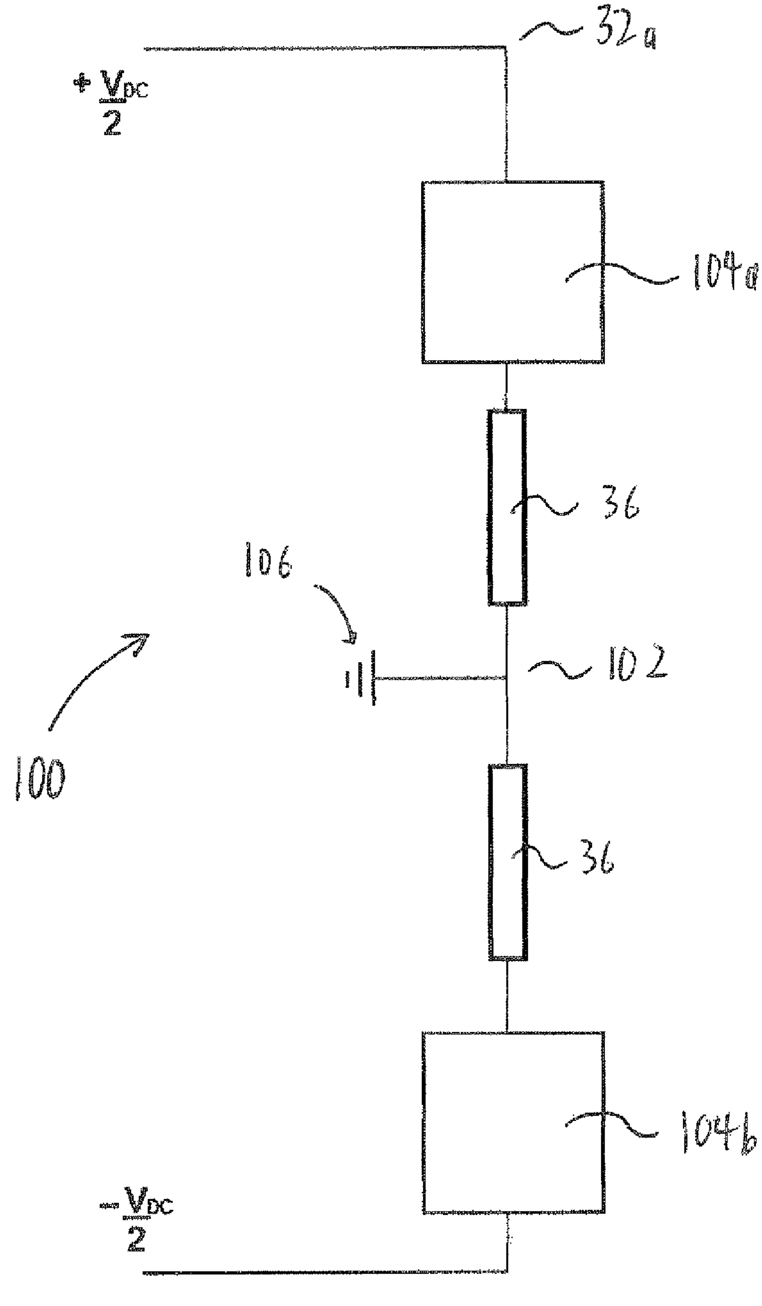


Figure 15

CONTROL CIRCUIT FOR DC NETWORK TO MAINTAIN ZERO NET CHANGE IN ENERGY LEVEL

CROSS-REFERENCE TO RELATED PATENT APPLICATION

The present application is a National Stage Application of International Application No. PCT/EP2011/069563 entitled "CONTROL CIRCUIT" filed Nov. 7, 2011, the contents of which are incorporated herein by reference in their entirety.

The invention relates to a control circuit.

In DC power transmission schemes, DC transmission lines **10***a*,**10***b* are used to interconnect a transmitting electrical network **12** and a receiving electrical network **14** to permit transfer of power between the two electrical networks **12**,**14**, as shown in FIG. **1**. In the event of a fault **16** preventing the receiving electrical network **14** from receiving power from the DC transmission lines **10***a*,**10***b*, the transmitting electrical network **12** cannot interrupt the transmission of power into the DC transmission lines **10***a*,**10***b*. This is because generators, such as wind turbines, cannot be switched off instantaneously and so will continue to feed energy **18** into the DC transmission lines **10***a*,**10***b*. Moreover, the receiving electrical network **14** is required by a Grid Code to ride through a supply dip, e.g. where the voltage is reduced to approximately 15% of its original value, and to resume the transmission of power upon the removal of the fault **16**.

Continuing to transmit power into the DC transmission lines **10***a*,**10***b* results in an accumulation of excess power in the DC transmission lines **10***a*,**10***b* which not only adversely affects the balance between the transmission and receipt of power by the respective electrical networks **12**,**14**, but also might damage various components of the DC power transmission scheme, particularly as a result of high voltage stress caused by uncontrolled charging of the capacitance of the DC transmission lines **10***a*,**10***b*.

One solution for preventing the accumulation of excess power is to temporarily store the excess power in DC link capacitors and other capacitors forming part of the transmitting electrical network **12**. The finite energy storage capability of the transmitting electrical network **12** however limits the amount of real power that may be temporarily stored away until the receiving electrical network **14** returns to its working state.

Another solution for preventing the accumulation of excess power is the use of a load dump chopper circuit **20** to divert the excess power away from the DC transmission lines **10***a*,**10***b*. FIG. **2** shows a dump resistor **22** connected in series with a switch **24** across the DC transmission lines **10***a*,**10***b*. Closing the switch **24** causes current to flow from the DC transmission lines through the dump resistor **22**, which in turn causes power to dissipate via the dump resistor **22**. This allows excess energy to be removed from the DC transmission lines **10***a*,**10***b* via the load dump chopper circuit **20**.

Existing chopper circuits utilise a simple semiconductor switch to connect a resistor between the DC transmission lines in order to absorb excess energy. This type of chopper relies on the series connection and simultaneous switching of a large number of lower voltage semiconductor switches which are operated in a pulse width modulation (PWM) manner to accurately control the energy absorption. The design and operation of such a chopper circuit switch requires large passive devices and complex control methods to ensure equal sharing of the total applied voltage between the individual semiconductor switches. In addition, the PWM action leads to very high rates of change of voltage and current within the

chopper circuit and DC transmission lines which leads to undesirable electrical spikes and a high level of electromagnetic noise and interference.

According to an aspect of the invention, there is provided a control circuit comprising first and second DC terminals for connection to a DC network, the first and second DC terminals having a plurality of modules and at least one energy conversion element connected in series therebetween to define a current transmission path, the plurality of modules defining a chain-link converter, each module including at least one energy storage device, the or each energy storage device being selectively removable from the current transmission path to cause a current waveform to flow from the DC network through the current transmission path and the or each energy conversion element and thereby remove energy from the DC network, the or each energy storage device being selectively removable from the current transmission path to modulate the current waveform to maintain a zero net change in energy level of the chain-link converter.

The ability to selectively remove the or each energy storage device of each module from the current transmission path has been found to allow a fast transfer of energy, i.e. excess power, from the DC network to the control circuit and thereby enables rapid regulation of the energy levels in the DC network. Such a DC network may include, but is not limited to, DC transmission lines of a DC power transmission scheme.

The modulation of the current waveform to maintain a zero net change in energy level of the chain-link converter maintains the average energy level of the chain-link converter at a constant value. This allows the individual voltage levels of the energy storage devices to be maintained at constant values before and after the operation of the control circuit to remove excess energy from the DC network. Otherwise a non-zero net change in energy level of the chain-link converter would require the use of additional bidirectional power transfer hardware to offset the increase or decrease in energy level of the chain-link converter. The use of additional bidirectional power transfer hardware however adds to the cost, size and weight of the control circuit.

To achieve a zero net change in energy level of the chain-link converter, any increase in energy level must be offset by a corresponding decrease in energy level over a single duty cycle of the control circuit. This may be achieved by selectively removing the energy storage devices from the current transmission path to construct either: a bidirectional voltage waveform across and a unidirectional current waveform through the chain-link converter; or a unidirectional voltage waveform across and a bidirectional current waveform through the chain-link converter. In either case, each energy storage device may be inserted into the current transmission path so that the current waveform flows in either forward or reverse directions through each energy storage device. This in turn allows selective real-time charging or discharging, and thereby control of the voltage level, of each energy storage device whilst the control circuit is controlled to remove excess real power from the DC network.

Such control of the voltage level of each energy storage device allows balancing of the individual voltage levels of the energy storage devices, and thereby simplifies the design of the control circuit by allowing, for example, the use of average voltage value as feedback to control selective removal of the energy storage devices from the current transmission path.

In embodiments of the invention each module may further include at least one switching element to selectively direct current through at least one energy storage device and cause current to bypass the or each energy storage device.

In such embodiments each module includes two pairs of switching elements connected in parallel with the or each energy storage device in a full-bridge arrangement to define a 4-quadrant bipolar module that can provide zero, positive or negative voltage and can conduct current in two directions.

In other such embodiments each module includes a pair of switching elements connected in parallel with the or each energy storage device in a half-bridge arrangement to define a 2-quadrant unipolar module that can provide zero or positive voltage and can conduct current in two directions.

In further such embodiments each module may include first and second sets of series-connected current flow control elements, each set of current flow control elements including a switching element to selectively direct current through the or each energy storage device and a passive current check element to limit current flow through the module to a single direction, the first and second sets of series-connected current flow control elements and the or each energy storage device being arranged in a full-bridge arrangement to define a 2-quadrant bipolar rationalised module that can provide zero, positive or negative voltage while conducting current in a single direction.

Such modules provide a reliable means of selectively removing the or each energy storage device from the current transmission path.

In embodiments employing the use of one or more switching elements at least one switching element may be or may include a semiconductor device.

In such embodiments, the or each semiconductor device may be an insulated gate bipolar transistor, a gate turn-off thyristor, a field effect transistor, an injection enhanced gate transistor or an integrated gate commutated thyristor.

Optionally at least one switching element further includes an anti-parallel diode connected in parallel with the or each corresponding semiconductor device.

The fast switching capabilities of such semiconductor devices helps the control circuit to respond quickly to changes in energy levels in the DC network, and also enables fine control over the selective removal of respective energy storage devices from the current transmission path. Moreover, the inclusion of such semiconductor devices permits the use of pulse width modulation, if desired.

Preferably the or each energy conversion element is or includes a resistor.

The resistance value may be adjusted to match the requirements of the control circuit, such as, for example, the rate of dissipation of excess energy flowing into the control circuit from the DC network.

In other embodiments of the invention the or each energy storage device may be or may include a capacitor, a battery, or a fuel cell.

A respective energy storage device may be any device that is capable of storing and releasing electrical energy to provide a voltage. This flexibility is useful in designing control circuits in different locations where the availability of equipment may be limited due to locality or transport difficulties.

In embodiments of the invention the control circuit may include a plurality of energy conversion elements connected in series with the plurality of modules.

Preferably the energy conversion elements and the modules are arranged to define an alternating sequence of energy conversion elements and modules.

Such arrangements result in a modular arrangement of the control circuit comprising a plurality of modular sections, each of which includes a module grouped with a neighbouring energy conversion element. This allows an apparatus associated with the control circuit to be divided into a plurality of modular sub-apparatus, each of which is linked to an individual modular section. Such an apparatus may be, for example, a thermal management unit. As such the control circuit is readily scalable to add or remove a modular section and its accompanying sub-apparatus without the need for substantial redesign and modification of the associated apparatus to correspond to the scale of the control circuit.

The control circuit may optionally further include a third terminal connected in series between the first and second DC terminals, the third terminal being for connection to ground, the plurality of modules including first and second sets of modules, the first set of modules being connected in series with at least one energy conversion element between the first DC terminal and the third terminal, the second set of modules being connected in series with at least one other energy conversion element between the second DC terminal and the third terminal.

Such an arrangement permits a different load to be applied to each of the first and second DC terminals connected to the DC network, if desired.

Preferably the control circuit further includes a controller to selectively remove each energy storage device from the current transmission path.

In embodiments of the invention the current waveform may include one or more current waveform components. In such embodiments the or each current waveform component may be selected from a group including, but not limited to, a half-sinusoidal current waveform component, a trapezoidal current waveform component, and higher order harmonic current waveform components.

The characteristics of the energy removed from the DC network varies with the shape of the current waveform.

It is preferred that the control circuit is capable of varying the amount of real power removed from the DC network to avoid over-voltage and under-voltage situations. This may be achieved by varying the shape of the current waveform in real-time. For example, the current waveform may be modulated to add or remove one or more current waveform components to vary the shape of the current waveform.

Optionally the current waveform is modulated to include a plurality of current pulses and add a time delay between consecutive current pulses. In such embodiments the durations of each current pulse and the time delay may be equal.

The use of a time delay in the current waveform reduces loading of the or each energy conversion element, if desired.

In other embodiments of the invention the voltage rating of the chain-link converter may be set to exceed the voltage of the DC network.

A higher voltage rating allows the chain-link converter to construct a voltage that exceeds the voltage across the DC network in order to reverse the direction of current in the current transmission path. This in turn permits the modulation of a current waveform to achieve the required zero net change in energy level of the chain-link converter in certain arrangements of the control circuit, in which the chain-link converter is capable of constructing a voltage in only one direction.

In further embodiments of the invention the or each energy storage device may be selectively removable from the current transmission path to charge one or more other energy storage devices.

This allows one or more energy storage devices to absorb real power from the DC network to offset any operating losses of the chain-link converter and thereby maintain the average energy level of the chain-link converter at a constant value without the need for additional power transfer hardware to add or remove energy.

Preferred embodiments of the invention will now be described, by way of non-limiting examples, with reference to the accompanying drawings in which:

FIGS. **1***a* and **1***b* show, in schematic form, prior art DC transmission schemes;

FIG. **2** shows, in schematic form, a control circuit according to a first embodiment of the invention;

FIGS. **3***a* and **3***b* illustrate characteristics of energy removed from the DC transmission lines using the control circuit of FIG. **2** when the current waveform flowing through the current transmission path and resistor is modulated to form a unidirectional, half-sinusoidal current waveform;

FIGS. **4***a* and **4***b* illustrate characteristics of energy removed from the DC transmission lines using the control circuit of FIG. **2** when the current waveform flowing through the current transmission path and resistor is modulated to add higher order harmonic components to a unidirectional, half-sinusoidal current waveform;

FIGS. **5***a* and **5***b* illustrate characteristics of energy removed from the DC transmission lines using the control circuit of FIG. **2** when the current waveform flowing through the current transmission path and resistor is modulated to form a unidirectional, trapezoidal current waveform;

FIG. **6** illustrates the modulation of the current waveform flowing through the current transmission path and resistor to vary its shape during the removal of energy from the DC transmission lines using the control circuit of FIG. **2**;

FIGS. **7***a* and **7***b* illustrate characteristics of energy removed from the DC transmission lines using the control circuit of FIG. **2** when the current waveform flowing through the current transmission path and resistor is modulated to add a time delay between consecutive half-sinusoidal current pulses;

FIGS. **8***a* and **8***b* illustrate characteristics of energy removed from the DC transmission lines using the control circuit of FIG. **2** when the current waveform flowing through the current transmission path and resistor is modulated to add a time delay between consecutive current pulses, where each current pulse includes a half-sinusoidal current component and 3^{rd}, 5^{th} and 7th higher order harmonic current components;

FIGS. **9***a* and **9***b* illustrate characteristics of energy removed from the DC transmission lines using the control circuit of FIG. **2** when the current waveform flowing through the current transmission path and resistor is modulated to add a time delay between consecutive trapezoidal current pulses;

FIGS. **10** and **11** show, in schematic form, a control circuit according to second and third embodiments of the invention respectively;

FIGS. **12***a* and **12***b* illustrate characteristics of energy removed from the DC transmission lines using the control circuit of FIG. **11** when the current waveform flowing through the current transmission path and resistor is modulated to form a bidirectional, half-sinusoidal current waveform;

FIGS. **13***a* and **13***b* illustrate characteristics of energy removed from the DC transmission lines using the control circuit of FIG. **11** when the current waveform flowing through the current transmission path and resistor is modulated to add a time delay between consecutive half-sinusoidal current pulses;

FIGS. **14** and **15** show, in schematic form, a control circuit according to fourth and fifth embodiments of the invention respectively.

A control circuit **30** according to a first embodiment of the invention is shown in FIG. **2**.

The first control circuit **30** comprises first and second DC terminals **32***a*,**32***b*.

In use, the first DC terminal **32***a* is connected to a first DC transmission line (not shown) that is at a positive voltage, $+V_{DC}/2$, while the second DC terminal **32***b* is connected to a second DC transmission line (not shown) that is at a negative voltage, $-V_{DC}/2$.

The first control circuit **30** further includes a plurality of modules **34** that are connected in series with a resistor **36** between the first and second DC terminals **32***a*,**32***b* to define a current transmission path. The resistor **36** is connected between the plurality of series-connected modules **34** and the second DC terminal **32***b*.

Optionally the resistor **36** may be connected between the plurality of series-connected modules **34** and the first DC terminal **32***a*.

Each module **34** includes two pairs of switching elements **38** connected in parallel with an energy storage device in the form of a capacitor **40**. The switching elements **38** and the capacitor **40** are connected in a full-bridge arrangement which defines a 4-quadrant bipolar module **34** that can provide a negative, zero or positive voltage and can conduct current in two directions

The capacitor **40** of each module **34** may be selectively removed from the current transmission path, i.e. switched in or out of circuit with the resistor **36**, by changing the state of the switching elements **38**. This allows the current in the first control circuit **30** to selectively flow through or bypass each capacitor **40**.

The capacitor **40** is removed from the current transmission path, i.e. switched out of circuit with the resistor **36**, when the pairs of switching elements **38** are configured to form a short circuit in the module **34**. This causes the current in the first control circuit **30** to pass through the short circuit and bypass the capacitor **40**. Such a configuration allows the module **34** to provide a zero voltage.

The capacitor **40** of each module **34** is returned to the current transmission path, i.e. switched back into circuit with the resistor **36**, when the pairs of switching elements **38** are configured to allow the current in the first control circuit **30** to flow into and out of the capacitor **40**. The capacitor **40** is then able to charge or discharge its stored energy and provide a voltage. The bidirectional nature of the 4-quadrant bipolar module **34** means that the capacitor **40** may be inserted into the 4-quadrant bipolar module **34** in either forward or reverse directions so as to provide a positive or negative voltage.

It is envisaged that the two pairs of switching elements **38** may be replaced by other configurations that are capable of selectively removing a corresponding energy storage device, e.g. a capacitor, from the current transmission path in the aforementioned manner.

Each switching element **38** includes an insulated gate bipolar transistor connected in parallel with an anti-parallel diode **42**. In other embodiments each switching element **38** may include a gate turn-off thyristor, a field effect transistor, an injection enhanced gate transistor or an integrated gate commutated thyristor, or other force-commutated or self-commutated semiconductor switches.

The size of the capacitor **40** of each module **34** may be reduced by switching the switching elements **38** at high frequencies, if desired. For example, when the DC transmission lines are operated at 100's of MW, the switching elements **38** of each module **34** may be switched at frequencies up to 500 Hz. This in turn reduces the size, weight and cost of the first control circuit **30**.

In still further embodiments each capacitor **40** may be replaced by another energy storage device such as a battery, or a fuel cell, or any device that is capable of storing and releasing electrical energy to provide a voltage.

The plurality of series-connected modules **34** defines a chain-link converter **44**. It is possible to build up a combined voltage across the chain-link converter **44**, which is higher than the voltage available from each individual module **34**, via the insertion of the capacitors **40** of multiple modules **34**, each providing its own voltage, into the chain-link converter **44**.

In this manner switching of the switching elements **38** of each 4-quadrant bipolar module **34** causes the chain-link converter **44** to provide a stepped variable voltage source, which permits the generation of a voltage waveform across the chain-link converter **44** using a step-wise approximation.

The first control circuit **30** further includes a controller (not shown), which switches the switching elements **38** in each module **34** to selectively remove the corresponding capacitor **40** from the current transmission path.

The operation of the first control circuit **30** shown in FIG. **2** within a DC power transmission scheme is described below.

First and second DC transmission lines interconnect first and second power converters that are themselves connected to respective phases of corresponding first and second AC networks (not shown). Power is transmitted from the first AC network to the second AC network via the corresponding power converters and the first and second DC transmission lines.

During normal operation the first control circuit **30** adopts a standby configuration in which the capacitor **40** of each module **34** is connected in the current transmission path, i.e. switched into circuit with the resistor **36**.

The total voltage across the modules **34** is approximately equal to V_{DC}, which is the voltage across the DC transmission lines. In this configuration there is zero or minimal current flowing through the current transmission path, i.e. through the resistor **36** and the modules **34**.

In the event that the second power converter is unable to receive the transmitted power as a result of, for example, a fault in the second AC network, the first AC network must temporarily continue transmitting power into the DC transmission lines until the power transfer can be reduced to zero, which is typically 1-2 seconds for a wind generation plant.

In order to allow the first AC network to continue transmitting power into the DC transmission lines via the first power converter, the controller selectively removes one or more capacitors **40** from the current transmission path. This results in the generation of a voltage waveform across the chain-link converter **44**, which adds or subtracts finite voltage steps to the voltage across the DC transmission lines, V_{DC}. This in turn imposes a voltage waveform across the resistor **36** and thereby causes a current waveform to flow from the DC transmission lines through the current transmission path and the resistor **36**.

Selective removal of each capacitor **40** from the current transmission path is carried out in accordance with Equation 1 to modulate the current waveform to maintain a zero net change in energy level of the chain-link converter **44** over each duty cycle of the first control circuit **30**. Modulating the current waveform in this manner offsets any increase in energy level with a corresponding decrease in energy level in each duty cycle of the first control circuit **30**, and vice versa.

$$P_{net} = \int_0^t (V_{CL} \times I_R) = 0 \tag{1}$$

Where

P_{net} is the net exchange of energy with the chain-link converter **44**

V_{CL} is the voltage across the chain-link converter **44**

I_R is the current flowing through the resistor **36** and chain-link converter **44**

t is the duration of each duty cycle of the first control circuit **30**

The flow of current through the resistor **36** enables excess energy in the DC transmission lines to be transferred to the first control circuit **30** and dissipated via the resistor **36**. The energy levels in the DC transmission lines are therefore regulated which helps to ensure power balance between each of the first and second AC networks and the first control circuit **30**.

The current waveform is modulated to form different shapes to vary characteristics of energy removed from the DC transmission lines, whilst maintaining a zero net change in energy level of the chain-link converter **44** over each duty cycle of the first control circuit **30**. Such characteristics include, but are not limited to, current flowing from the DC transmission lines through the current transmission path and resistor **36**, and amount of energy and power dissipated via the resistor **36**.

The current waveform may be modulated to form different shapes by including one or more current components having different current characteristics.

FIGS. **3***a* and **3***b* illustrate the characteristics of energy removed from the DC transmission lines using the first control circuit **30** of FIG. **2** when the current waveform flowing through the current transmission path and resistor **36** is modulated to form a unidirectional, half-sinusoidal current waveform **46***a*.

In order to form such a current waveform **46***a*, the controller selectively removes each capacitor **40** from the current transmission path to generate a bidirectional, half-sinusoidal voltage waveform **48***a* across the chain-link converter **44**. Accordingly this causes a unidirectional, half-sinusoidal current waveform **46***a* to flow from the DC transmission lines through the current transmission path and the resistor **36**, which in turn causes power to be dissipated via the resistor **36**.

FIG. **3***b* illustrates the corresponding instantaneous power **50***a* and average power **52***a* dissipated via the resistor **36** over each duty cycle of the first control circuit **30**. The instantaneous power **50***a* dissipated via the resistor **36** during each duty cycle is given by the product of the instantaneous current flowing through the resistor **36** and the instantaneous voltage across the resistor **36**. The average power **52***a* dissipated via the resistor **36** is given by the product of the average current flowing through the resistor **36** and the average voltage across the resistor **36**. It is shown that when V_{DC} is 10 kV, the average power **52***a* dissipated via the resistor **36** is 10 MW.

For the half-sinusoidal current waveform **46***a*, the average current flowing through the resistor **36** is given by the product of $2/\pi$ and the peak current flowing through the resistor **36**. Thus, when V_{DC} is 10 kV and the average current flowing through the resistor **36** is 1 kA, the peak current flowing through the resistor **36** is 1.57 kA.

FIGS. **4***a* and **4***b* illustrate the characteristics of energy removed from the DC transmission lines using the first control circuit **30** of FIG. **2** when the current waveform **46***b* flowing through the current transmission path and resistor **36** is modulated to add higher order harmonic components to a unidirectional, half-sinusoidal current waveform.

In order to form such a current waveform **46***b*, the controller selectively removes each capacitor **40** from the current transmission path to generate a bidirectional voltage waveform **48**_b_ across the chain-link converter **44**, where the voltage waveform **48**_b_ includes a half-sinusoidal voltage component and its corresponding 3^{rd}, 5^{th} and 7^{th} harmonic voltage components. Accordingly this causes a unidirectional, harmonically modulated current waveform **46**_b_ to flow from the DC transmission lines through the current transmission path and the resistor **36**, where the current waveform **46**_b_ includes a half-sinusoidal current component together with its corresponding 3^{rd}, 5^{th} and 7^{th} harmonic current components, and thereby causes power to be dissipated via the resistor **36**.

FIG. **4**_b_ illustrates the corresponding instantaneous power **50**_b_ and average power **52**_b_ dissipated via the resistor **36** over each duty cycle of the first control circuit **30**. It is shown that, when V_{DC} is 10 kV, the average power **52**_b_ dissipated via the resistor **36** remains unchanged, i.e. the average power **52**_b_ dissipated via the resistor **36** is 10 MW. The current waveform **46**_b_ flowing through the resistor **36** however has a lower peak current of 1.24 kA flowing through the resistor **36** when compared to the half-sinusoidal current waveform **46**_a_.

FIGS. **5**_a_ and **5**_b_ illustrate the characteristics of energy removed from the DC transmission lines using the first control circuit **30** of FIG. **2** when the current waveform flowing through the current transmission path and resistor **36** is modulated to form a unidirectional, trapezoidal current waveform **46**_c_.

In order to form such a current waveform **46**_c_, the controller removes each capacitor **40** from the current transmission path to generate a bidirectional, trapezoidal voltage waveform **48**_c_ across the chain-link converter **44**. Accordingly this causes a unidirectional, trapezoidal current waveform **46**_c_ to flow from the DC transmission lines through the current transmission path and the resistor **36**, and thereby causes power to be dissipated via the resistor **36**.

FIG. **5**_b_ illustrates the corresponding instantaneous power **50**_c_ and average power **52**_c_ dissipated via the resistor **36** over each duty cycle of the first control circuit **30**. It is shown that, when V_{DC} is 10 kV, the average power **52**_c_ dissipated via the resistor **36** remains unchanged, i.e. the average power **52**_c_ dissipated via the resistor **36** is 10 MW. The current waveform **46**_c_ flowing through the resistor **36** has a lower peak current of 1.11 kA flowing through the resistor **36** when compared to the half-sinusoidal and harmonically modulated current waveforms **46**_a_,**46**_b_.

The modulation of the current waveform to form a either harmonically modulated or trapezoidal waveform **46**_b_,**46**_c_ therefore results in a lower peak current to average current ratio when compared to the half-sinusoidal current waveform **46**_a_, without affecting the amount of energy and power removed from the DC transmission lines. This has the benefit of reducing the current rating required of the first control circuit **30**.

FIG. **6** illustrates the modulation of the current waveform flowing through the current transmission path and resistor **36** to vary its shape during the removal of energy from the DC transmission lines using the first control circuit **30** of FIG. **2**.

As described above with reference to FIGS. **4**_a_ and **4**_b_, when V_{DC}=10 kV, harmonically modulating the current waveform to add higher order harmonic components to a half-sinusoidal current waveform results in a peak current of 1.24 kA flowing through the resistor **36**, an average current of 1 kA flowing through the resistor **36**, and 10 MW of average power **52**_b_ dissipated via the resistor **36**.

The shape of the current waveform is varied when the controller selectively removes one or more capacitors **40** from the current transmission path to modulate the harmonically modulated current waveform **54**_a_ by removing the higher order harmonic components to form a half-sinusoidal current waveform **54**_b_ flowing through the resistor **36** with a peak current of 1.24 kA. This in turn causes the average current flowing through the resistor **36** to reduce to 790 A and the average power dissipated via the resistor **36** to reduce to 7.9 MW.

Thus, for a given current rating of the chain-link converter **44**, the current waveform may be modulated to add or remove one or more current components to change its shape and vary the average power dissipated via the resistor **36** in real-time. The first control circuit **30** is thus able to vary the amount of real power removed from the DC transmission lines in response to real-time changes in power levels of the DC transmission scheme to avoid over-voltage and under-voltage situations.

Optionally the current waveform flowing through the current transmission path and resistor **36** may be modulated to include a plurality of current pulses and add a time delay between consecutive current pulses.

FIGS. **7** to **9** illustrate the characteristics of energy removed from the DC transmission lines using the first control circuit **30** of FIG. **2** when the current waveform **46**_d_,**46**_e_,**46**_f_ flowing through the current transmission path and resistor **36** is modulated to add a time delay **56** between consecutive current pulses **58**_a_,**58**_b_,**58**_c_ so that the durations of each current pulse **58**_a_,**58**_b_,**58**_c_ and each time delay **56** are equal, i.e. a 50:50 duty cycle ratio.

In further embodiments it is envisaged that the durations of each current pulse **58**_a_,**58**_b_,**58**_c_ and each time delay **56** may be changed to define a different duty cycle ratio.

Each current pulse **58**_a_ in FIG. **7**_a_ and each resultant power pulse in FIG. **7**_b_ includes a half-sinusoidal current component, each current pulse **58**_b_ in FIG. **8**_a_ and each resultant power pulse in FIG. **8**_b_ includes a half-sinusoidal current component and 3^{rd}, 5^{th} and 7th higher order harmonic current components, and each current pulse **58**_c_ in FIG. **9**_a_ and each resultant power pulse in FIG. **9**_b_ includes a trapezoidal current component.

It was found in each case that the addition of a time delay **56** between consecutive current pulses **58**_a_,**58**_b_,**58**_c_ of the current waveform **46**_d_,**46**_e_,**46**_f_ results in a lower average power **52**_d_,**52**_e_,**52**_f_ of 5 MW dissipated via the resistor **36** when compared to the previous current waveforms **46**_a_,**46**_b_, **46**_c_ omitting the time delay **56**. The use of a time delay **56** between consecutive current pulses **58**_a_,**58**_b_,**58**_c_ of the current waveform **46**_d_,**46**_e_,**46**_f_ has the benefit of reducing loading of the resistor **36**, if desired.

Following the removal of excess energy from the DC transmission lines through power dissipation via the resistor **36**, the controller switches the switching elements **38** of the modules **34** to switch each capacitor **40** back into circuit with the resistor **36**. Such a configuration turns off the current flowing in the first control circuit **30**, which allows the DC transmission scheme to revert to normal operation.

It is shown in FIGS. **3** to **9** that any increase **60**_a_ in energy level of the chain-link converter **44** is offset by a corresponding decrease **60**_b_ in energy level in the same duty cycle, and vice versa. Thus, the modulation of the current waveform in accordance with Equation 1 to form different shapes to vary the characteristics of energy removed from the DC transmission lines maintains a zero net change in energy level of the chain-link converter **44** over each duty cycle of the first control circuit **30**, i.e. the energy level of the chain-link converter **44** is the same before and after the operation of the first control circuit **30** to remove energy from the DC transmission lines. Accordingly the individual voltage levels of the capacitors **40** may be maintained at constant values before and after the operation of the first control circuit **30** to remove energy from the DC transmission lines.

In contrast, a non-zero net change in energy level of the chain-link converter **44** would result in a increase or decrease in energy level of the chain-link converter **44** over time, and thereby cause an increase or decrease in voltage level of one or more capacitors **40**. It is possible to offset the increase or decrease in energy level of the chain-link converter **44** by using bidirectional power transfer hardware to add or remove energy to each capacitor **40**. However, such use adds to the overall size, weight and cost of the first control circuit **30**.

In addition, the shape of the current waveform modulated to maintain a zero net change in energy level of the chain-link converter **44** permits the insertion of a capacitor **40** into the current transmission path so that the current waveform flows in either forward or reverse directions through the capacitor **40**. This in turn allows selective real-time charging or discharging, and thereby control of the voltage level, of a capacitor **40** whilst the first control circuit **30** is controlled to remove energy from the DC transmission lines.

Such control of the voltage level of a capacitor **40** allows balancing of the individual voltage levels of the capacitors **40**, and thereby simplifies the design of the first control circuit **30** by allowing, for example, the use of average voltage value as feedback to control selective removal of the capacitors **40** from the current transmission path.

Moreover the use of the chain-link converter **44** to modulate the current waveform improves control over the rates of change of voltage and current, dv/dt and di/dt, in the first control circuit **30** and thereby avoids fast dv/dt and di/dt transients, which complicates the design of the chain-link converter **44** and create unwanted noise and electromagnetic interference.

The controller may switch the switching elements **38** of the modules **34** to selectively remove one or more capacitors **40** from the current transmission path to charge one or more other capacitors **40**. In this way the capacitors **40** are able to selectively absorb real power from the DC transmission lines to offset any operating losses of the chain-link converter **44** and thereby maintain the average energy level of the chain-link converter **44** at a constant value.

A control circuit **70** according to a second embodiment of the invention is shown in FIG. **10**. The second embodiment of the control circuit **70** shown in FIG. **10** is similar in terms of structure and operation to the first embodiment of the control circuit **30** in FIG. **2**, and like features share the same reference numerals.

The second control circuit **70** differs from the first control circuit **30** in that each module **72** includes first and second sets **74*a***,**74*b*** of series-connected current flow control elements. Each set **74*a***,**74*b*** of current flow control elements includes a switching element **38** to selectively direct current through an energy storage device in the form of a capacitor **40**, and a passive current check element in the form of a diode **76** to limit current flow through the module **72** to a single direction. Each switching element **38** includes an insulated gate bipolar transistor connected in parallel with an anti-parallel diode **42**.

The first and second sets **74*a***,**74*b*** of series-connected current flow control elements and the capacitor **40** are arranged in a full-bridge arrangement to define a 2-quadrant bipolar rationalised module **72** that can provide zero, positive or negative voltage while conducting current in a single direction.

As with the first control circuit **30**, the current waveform flowing through the current transmission path and resistor **36** of the second control circuit **70** may be modulated in accordance with Equation 1 to form different waveform shapes to vary characteristics of energy removed from the DC transmission lines, in particular waveform shapes to vary characteristics of energy removed from the DC transmission lines in a similar manner to that of FIGS. **3** to **9**.

The unidirectional nature of the current waveform flowing through the current transmission path and the resistor **36** means that the operation of the second control circuit **70** to remove energy from the DC transmission lines is unaffected by the use of the 2-quadrant bipolar rationalised modules **72**, instead of the 4-quadrant bipolar modules **34**, in the second control circuit **70**. This has the benefit of reducing the size, weight and cost of the chain-link converter **44**.

A control circuit **80** according to a third embodiment of the invention is shown in FIG. **11**. The third embodiment of the control circuit **80** shown in FIG. **11** is similar in terms of structure and operation to the first embodiment of the control circuit **30** in FIG. **2**, and like features share the same reference numerals.

The third control circuit **80** differs from the first control circuit **30** in that each module **82** includes a pair of switching elements **38** connected in parallel with a energy storage device in a half-bridge arrangement to define a 2-quadrant unipolar module **82** that can provide zero or positive voltage and can conduct current in two directions. Each switching element **38** includes an insulated gate bipolar transistor connected in parallel with an anti-parallel diode **42**, while each energy storage device is in the form of a capacitor **40**.

The voltage rating of the chain-link converter **44** is set to exceed the voltage across the DC transmission lines, V_{DC}. When the chain-link converter **44** provides a voltage that is less than the voltage across the DC transmission lines, the current waveform flows through the current transmission path and resistor **36** from the first DC transmission line, which is at $+V_{DC}/2$ to the second DC transmission line, which is at $-V_{DC}/2$. When the chain-link converter **44** provides a voltage that exceeds the voltage across the DC transmission lines, the current waveform flows through the current transmission path and resistor **36** from the second DC transmission line, which is at $-V_{DC}/2$, to the first DC transmission line, which is at $+V_{DC}/2$.

Accordingly the controller may switch the switching elements **38** of the 2-quadrant unipolar modules **82** to selectively remove one or more capacitors **40** from the current transmission path to cause a bidirectional current waveform to flow from the DC transmission lines through the current transmission path and resistor **36**, whilst the chain-link converter **44** provides a unidirectional voltage waveform. This permits modulation of the current waveform in accordance with Equation 1 to maintain a zero net change in energy level of the chain-link converter **44**.

As with the first and second control circuits **30**,**70**, the current waveform flowing through the current transmission path and resistor **36** of the third control circuit **80** may be modulated in accordance with Equation 1 to form different waveform shapes to vary characteristics of energy removed from the DC transmission lines.

FIGS. **12*a*** and **12*b*** illustrate the characteristics of energy removed from the DC transmission lines using the third control circuit **80** of FIG. **11** when the current waveform flowing through the current transmission path and resistor **36** is modulated to form a bidirectional, half-sinusoidal current waveform **46*g***.

In order to form such a current waveform **46*g***, the controller selectively removes each capacitor **40** from the current transmission path to generate a unidirectional, half-sinusoidal voltage waveform **48*g*** across the chain-link converter **44**, where the voltage waveform **48*g*** exceeds V_{DC} over part of each duty cycle. Accordingly this causes a bidirectional, half-sinusoidal current waveform **46***g* to flow from the DC transmission lines through the current transmission path and the resistor **36**.

FIG. **12***b* illustrates the corresponding instantaneous power **50***g* and average power **52***g* dissipated via the resistor **36** over each duty cycle of the third control circuit **80**. It is shown that, when V_{DC} is 10 kV, the average power **52***g* dissipated via the resistor **36** is 10 MW. In this case the chain-link converter **44** has a voltage rating that is 27% higher than the voltage across the DC transmission lines, V_{DC}.

FIGS. **13***a* and **13***b* illustrate the characteristics of energy removed from the DC transmission lines using the third control circuit **80** of FIG. **11** when the current waveform **46***h* flowing through the current transmission path and resistor **36** is modulated to add a time delay **56** between consecutive half-sinusoidal current pulses **58***d* so that the durations of each current pulse **58***d* and each time delay **36** are equal, i.e. a 50:50 duty cycle. It is shown that, when V_{DC} is 10 kV, the average power **52***h* dissipated via the resistor **36** is 5 MW.

It is envisaged that in other embodiments the controller may selectively remove each capacitor **40** from the current transmission path to modulate the current waveform to include higher order harmonic components, or form a trapezoidal current waveform or other types of current waveforms.

A control circuit **90** according to a fourth embodiment of the invention is shown in FIG. **14**. The fourth embodiment of the control circuit **90** shown in FIG. **14** is similar in terms of structure and operation to the first embodiment of the control circuit **30** in FIG. **2**, and like features share the same reference numerals.

The fourth control circuit **90** differs from the first control circuit **30** in that the fourth control circuit **90** includes a plurality of resistors **36** connected in series with the plurality of modules **34** between the first and second DC terminals **32***a*,**32***b*. The resistors **36** and the modules **34** are arranged to define an alternating sequence of resistors **36** and modules **34**.

Such an arrangement is advantageous in that each module **34** is grouped with a neighbouring resistor **36** to define a modular section **92** so that the fourth control circuit **90** consists of a plurality of modular sections **92**. This allows a thermal management unit (not shown) linked to each module **34** to also be linked to the corresponding resistor **36** in the same modular section **92**. Otherwise it would be necessary to install a single, separate thermal management unit for use with the plurality of resistors **36**.

The modular arrangement of the fourth control circuit **90** means that it is readily scalable to increase its voltage rating. In contrast, the use of the above single, separate thermal management unit would require substantial redesign and modification of the thermal management unit to correspond to the scale of the fourth control circuit **90**.

A control circuit **100** according to a fifth embodiment of the invention is shown in FIG. **15**. The fifth embodiment of the control circuit **100** shown in FIG. **15** is similar in terms of structure and operation to the first embodiment of the control circuit **30** in FIG. **2**, and like features share the same reference numerals.

The fifth control circuit **100** differs from the first control circuit **30** in that the fifth control circuit **100** further includes a third terminal **102** connected in series between the first and second DC terminals **32***a*,**32***b*. The plurality of modules is divided into first and second sets of modules **104***a*,**104***b*. The first set of modules **104***a* is connected in series with a resistor **36** between the first DC terminal **32***a* and the third terminal **102**, while the second set of modules **104***b* is connected in series with another resistor **36** between the second DC terminal **32***b* and the third terminal **102**. In use, the third terminal **102** may be connected to ground **106**.

Such an arrangement permits a different load to be applied to each of the first and second DC terminals **32***a*,**32***b* connected to the DC transmission lines, if desired.

The invention claimed is:

1. A control circuit comprising first and second DC terminals for connection to a DC network, the first and second DC terminals having a plurality of modules and at least one energy conversion element connected in series therebetween to define a current transmission path, the plurality of modules defining a chain-link converter, each module including at least one energy storage device, the at least one energy storage device being selectively removable from the current transmission path to cause a current waveform to flow from the DC network through the current transmission path and the at least one energy conversion element and thereby remove energy from the DC network, the at least one energy storage device being selectively removable from the current transmission path to modulate the current waveform to maintain a zero net change in energy level of the chain-link converter, each module further including:

a) two pairs of switching elements connected in parallel with the at least one energy storage device in a full-bridge arrangement to define a 4-quadrant bipolar module that can provide zero, positive or negative voltage and can conduct current in two directions, or

b) first and second sets of series-connected current flow control elements, each set of current flow control elements including a switching element to selectively direct current through the or each energy storage device and a passive current check element to limit current flow through the module to a single direction, the first and second sets of series-connected current flow control elements and the or each energy storage device being arranged in a full-bridge arrangement to define a 2-quadrant bipolar rationalized module that can provide zero, positive or negative voltage while conducting current in a single direction.

2. A control circuit according to claim **1**, wherein at least one switching element is or includes a semiconductor device.

3. A control circuit according to claim **2**, wherein the or each semiconductor device is an insulated gate bipolar transistor, a gate turn-off thyristor, a field effect transistor, an injection enhanced gate transistor or an integrated gate commutated thyristor.

4. A control circuit according to claim **2** wherein at least one switching element further includes an anti-parallel diode connected in parallel with the or each corresponding semiconductor device.

5. A control circuit according to claim **1** wherein the or each energy conversion element is or includes a resistor.

6. A control circuit according to claim **1** wherein the or each energy storage device is or includes a capacitor, a battery, or a fuel cell.

7. A control circuit according to claim **1** including a plurality of energy conversion elements connected in series with the plurality of modules.

8. A control circuit according to claim **7** wherein the energy conversion elements and the modules are arranged to define an alternating sequence of energy conversion elements and modules.

9. A control circuit according to claim **7** further including a third terminal connected in series between the first and second DC terminals, the third terminal being for connection to ground, the plurality of modules including first and second sets of modules, the first set of modules being connected in series with at least one energy conversion element between the first DC terminal and the third terminal, the second set of modules being connected in series with at least one other energy conversion element between the second DC terminal and the third terminal.

10. A control circuit according to claim **1** further including a controller to selectively remove each energy storage device from the current transmission path.

11. A control circuit according to claim **1** wherein the current waveform includes one or more current waveform components.

12. A control circuit according to claim **11** wherein the or each current waveform component is selected from a group including a half-sinusoidal current waveform component, a trapezoidal current waveform component, and higher order harmonic current waveform components.

13. A control circuit according to claim **11** wherein the current waveform is modulated to add or remove one or more current waveform components.

14. A control circuit according to claim **1** wherein the current waveform is modulated to include a plurality of current pulses and add a time delay between consecutive current pulses.

15. A control circuit according to claim **14** wherein the durations of each current pulse and the time delay are equal.

16. A control circuit according to claim **1** wherein the voltage rating of the chain-link converter is set to exceed the voltage of the DC network.

17. A control circuit according to claim **1** wherein the or each energy storage device is selectively removable from the current transmission path to charge one or more other energy storage devices.

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